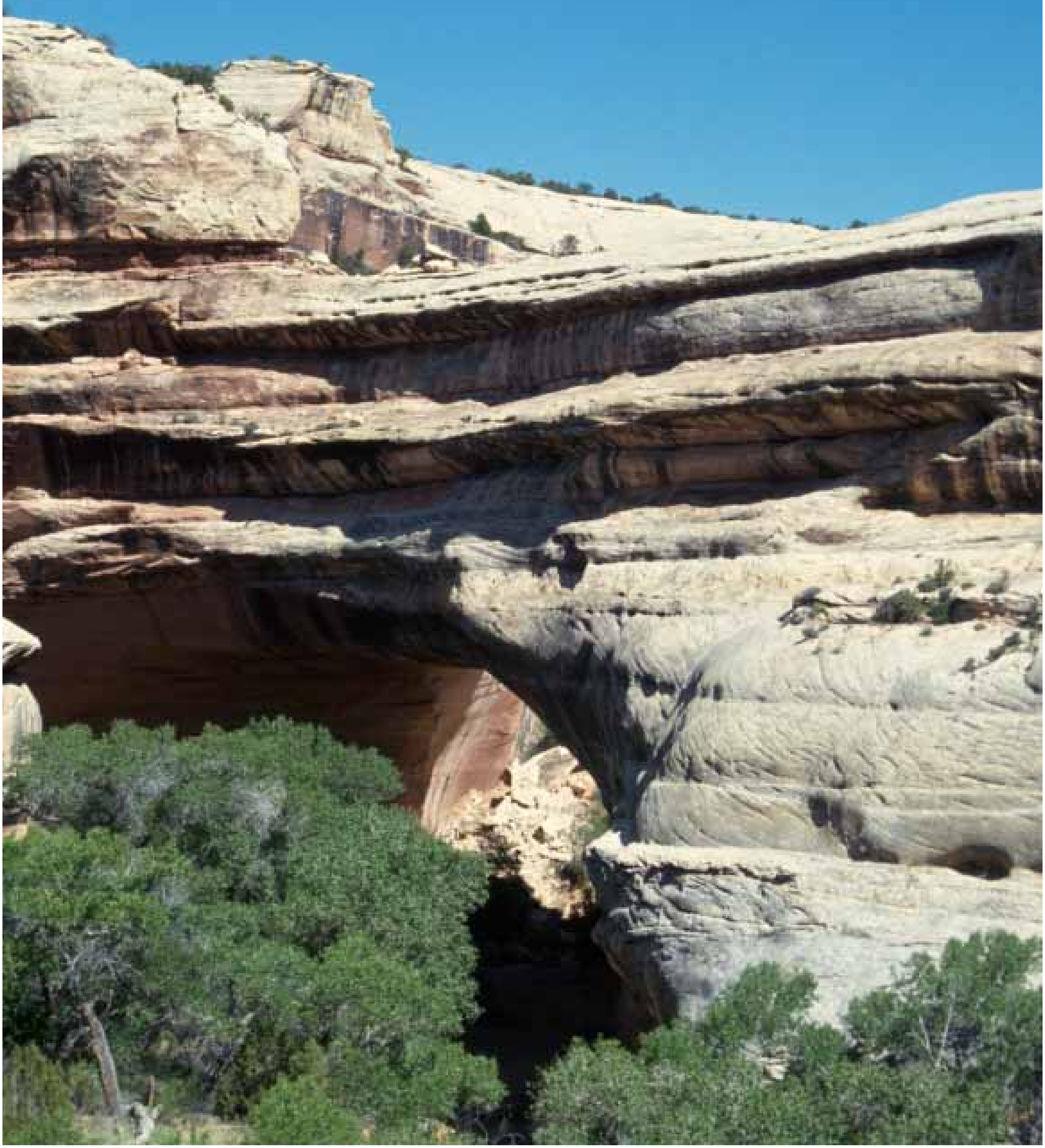
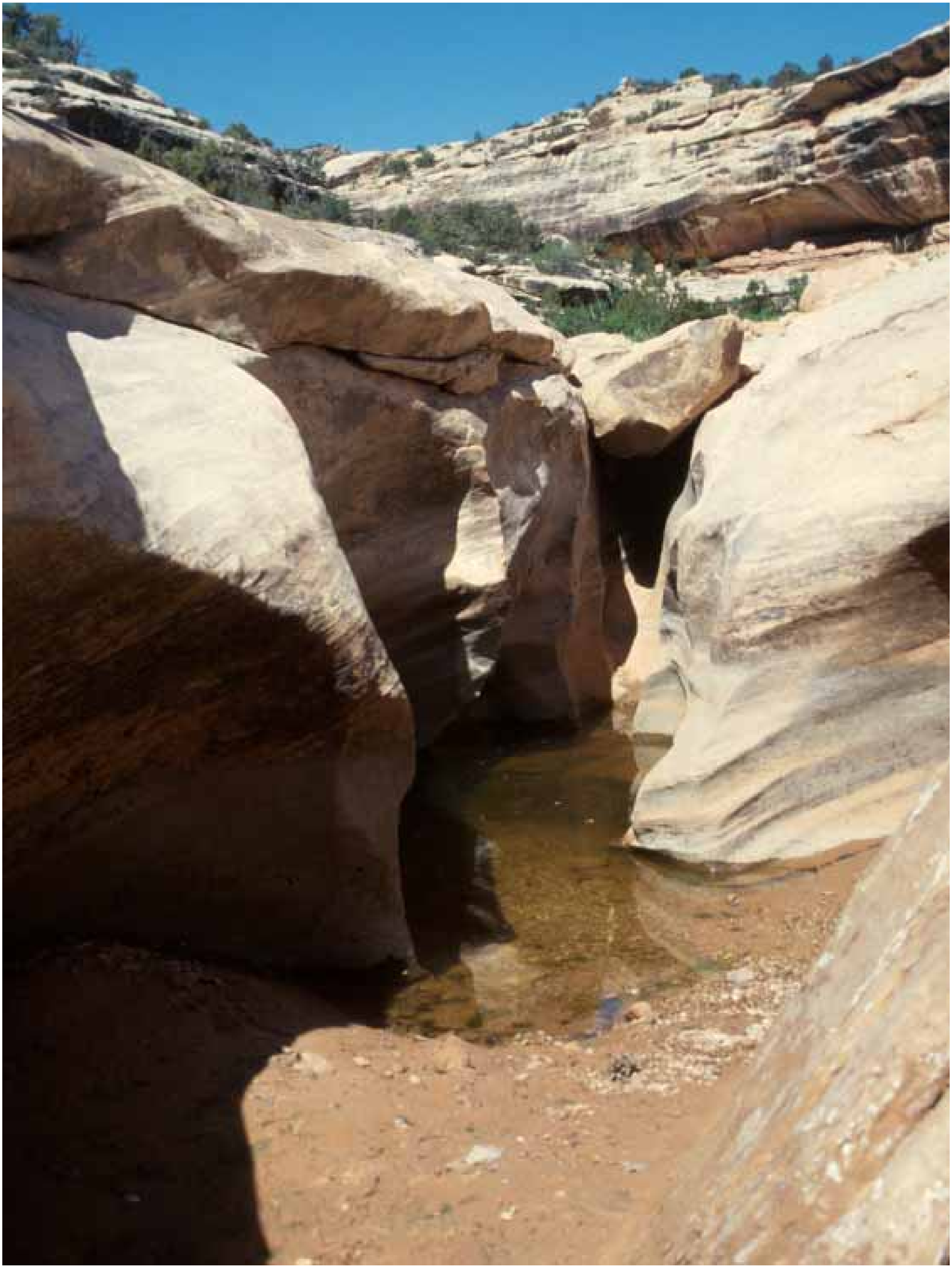
National Park Service
U.S. Department of the Interior

Geologic Resources Division
Denver, Colorado

Natural Bridges National Monument

Geologic Resource Evaluation Report





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Geologic Resource Evaluation

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Executive Summary

This report has been developed to accompany the digital geologic map produced by Geologic Resource Evaluation staff for Natural Bridges National Monument in Utah. It contains information relevant to resource management and scientific research.

Geology provides the foundation of the entire ecosystem. One stratigraphic unit of rock dominates the geology of Natural Bridges, the sandstone of the Permian age Cedar Mesa Formation. Meandering streams have cut down through the Cedar Mesa Sandstone since the regional uplift of the Colorado Plateau, a geologic province of high plateaus and broad, rounded uplands separated by vast rangelands encompassing most of southern Utah and northern Arizona, northwest New Mexico, and western Colorado. In places these streams have cut through canyon walls at a sharp meander bend, forming the three natural bridges for which the park was designated. As the name suggests, Natural Bridges National Monument hosts some of the largest natural bridge geologic features on earth. It is not surprising then that some of the principal geologic issues and concerns pertain to protecting these features.

The seven geologic units specifically associated with the monument include unconsolidated Quaternary age alluvium, Jurassic age Wingate Sandstone, Triassic age Chinle and Moenkopi Formations, Permian age Organ Rock and Cedar Mesa Formations and Permian to Pennsylvanian age Lower Cutler Beds (informal unit). These units are present at the monument in relatively flat lying, undisturbed layers. Erosion and weathering create the dramatic canyons, arches, and bridges. It is the interaction of the variety of rock types with the landscape created by uplift and erosion that must be understood to assess potential hazards and best protect the environment and the visitors to the monument. The Formation Properties section (see page 16) details the different units and potential resources, concerns and issues associated with each.

Humans have modified the desert landscape surrounding Natural Bridges and consequently have modified its geologic system. This system is dynamic and capable of noticeable change within a human life span (less than a century).

The following features, issues, and processes were identified as having the most geological importance and the highest level of management significance to the park:

- Bridge collapse. The monument was created to preserve and protect some of the largest natural bridges in the world. In the dynamic desert system, these features are at risk. Owachomo Bridge in the monument is only 3 m (9 ft) thick at the crest of its long span.

- The region around Natural Bridges National Monument is still seismically active making partial or total collapse a potential hazard.

- Slope failures and surficial processes. Desert environments are especially susceptible to slumping and landslides due to the lack of stabilizing plant growth. Intense seasonal storms produce flash floods that dramatically alter the landscape, creating new hazard areas in the process. Road and trail construction also impacts the stability of a slope. Predominantly mudstone units such as the Moenkopi Formation typically form slopes which are prone to fail when saturated with water. In addition to this hazardous situation, the Moenkopi is overlain by the cliff forming Chinle Formation. When the Chinle is undercut by erosion, large blocks of the overlying jointed sandstone can collapse. Rockfalls and slope failure are likely almost anywhere these units are exposed.

- Uranium and other mining issues. Copper and uranium mines dot the landscape around Natural Bridges National Monument, especially in White Canyon, Red Canyon and Deer Flats. Soil and water contamination associated with these abandoned mines are a serious hazard. Uranium also appears in the Triassic age Chinle Formation, exposed throughout the monument.

- Streamflow and channel morphology. In the arid climate of southern Utah, intense, short duration, seasonal rainstorms and subsequent flash floods may impact channel morphology. These intense seasonal events also result in changes in the load and deposition of sediment in the canyons. These changes affect aquatic and riparian ecosystems. Sediment loading and aggradation of the stream can result in changes to channel morphology and overbank flooding frequency. The canyons are also discharge points for local groundwater flow systems.

- Water Issues. Southern Utah receives an average of only 8 to 10 inches of precipitation per year. This defines the semi- arid to arid climate that makes water such an important resource. Water for the monument comes only from the Cedar Mesa Formation aquifer. Other available aquifers are too saline for drinking. The Cedar Mesa unit is exposed at the surface making the aquifer susceptible to contamination.
- Scant data exists regarding the capacity and hydrogeology of the aquifer system. This lack of information and monitoring makes managing the water resources at Natural Bridges very difficult.

Other geologic parameters and issues such as swelling clays, noise pollution, desert crusts, wind erosion and deposition, oil and gas exploration, and air pollution, were also identified during scoping sessions as critical management issues for Natural Bridges National Monument.

Introduction

The following section briefly describes the regional geologic setting and the National Park Service Geologic Resources Evaluation program.

Purpose of the Geologic Resources Evaluation Program

Geologic features and processes serve as the foundation of park ecosystems and an understanding of geologic resources yields important information needed for park decision making. The National Park Service Natural Resource Challenge, an action plan to advance the management and protection of park resources, has focused efforts to inventory the natural resources of parks. Ultimately, the inventory and monitoring of natural resources will become integral parts of park planning, operation and maintenance, visitor protection, and interpretation. The geologic component is carried out by the Geologic Resource Evaluation (GRE) Program administered by the NPS Geologic Resource Division. The goal of the GRE Program is to provide each of the identified 274 "Natural Area" parks with a digital geologic map, a geologic resource evaluation report, and a geologic bibliography. Each product is a tool to support the stewardship of park resources and is designed to be user friendly to non- geoscientists.

The GRE teams hold scoping meetings at parks to review available data on the geology of a particular park and to discuss the specific geologic issues in the park. Park staff are afforded the opportunity to meet with the experts on the geology of their park. Scoping meetings are usually held at each park to expedite the process although some scoping meetings are multipark meetings for an entire Vital Signs Monitoring Network.

Bedrock and surficial geologic maps and information provide the foundation for studies of groundwater, geomorphology, soils, and environmental hazards. Geologic maps describe the underlying physical habitat of many natural systems and are an integral component of the physical inventories stipulated by the National Park Service (NPS) in its Natural Resources Inventory and Monitoring Guideline (NPS- 75) and the 1997 NPS Strategic Plan. The NPS Geologic Resources Evaluation (GRE) is a cooperative implementation of a systematic, comprehensive inventory of the geologic resources in National Park System units by the Geologic Resources Division, the Inventory and Monitoring (I&M) Program of the Natural Resource Information Division, the U.S. Geological Survey, and state geological surveys.

For additional information regarding the content of this report please refer to the Geologic Resources Division of the National Park Service, located in Denver, Colorado with up- to- date contact information at the following website:
http://www.nature.nps.gov/grd

Geologic Setting

In 1904, *National Geographic* referred to the 'Colossal Bridges of Utah', grabbing the public interest in the first decade of the 20th Century. Theodore Roosevelt established Natural Bridges as Utah's first National Monument on April 16, 1908, to protect both the natural bridges and the archaeological ruins in the area (Huntoon *et al.*, 2000). The primary natural resources of the park are the bridges, cliffs, canyons, springs, and surface water.

This park is part of the Geologic Resource Evaluation Program because of the unique geologic resources and human impacts to these resources. Information gathered at this park may also be used to represent other parks with similar resources or patterns of use, especially when the findings are evaluated for Servicewide implications

At an average elevation of 2,000 m (6,500 ft) above sea level, the 7,636.49 acres of Natural Bridges National Monument are located on a high pinyon- juniper mesa bisected by deep canyons. The monument, located in southeastern Utah, is part of a geological feature called the Colorado Plateau Province (figure 1). Covering parts of Colorado, Utah, Arizona, and New Mexico, the Colorado Plateau is a region of high plateaus and broad, rounded uplands separated by vast rangelands. The rangelands are underlain by large elliptical stratigraphic basins.

The structural fabric of gently warped, rounded folds contrasts with the intense deformation and faulting of the terranes bordering the Colorado Plateau. Northeast and east of the Colorado Plateau are the jagged peaks of the Rocky Mountains. The Mesozoic- age overthrust belt marks the west- northwest edge of the Colorado Plateau (figure 1). The extensional, normal- faulted Basin and Range Province borders the Colorado Plateau to the west and south. The Rio Grande Rift, tearing a ragged scar in the landscape, forms the southeast border.

The Colorado Plateau is also known for its laterally extensive monoclines that formed during the Late Cretaceous – Tertiary (figure 1). The basins adjacent to the steep limbs of the monoclines have been filled with sediment eroded from these folds. The La Sal Mountains and the Abajo Mountains lie north of Natural Bridges National Monument, the Ute Mountains lie to the east, and the Carrizo Mountains are south, across the border into Arizona.

The bridges and other features present on the Colorado Plateau today were molded by the processes of erosion. The destructive forces of wind and rain, running water, and freezing temperatures attacked the uplifts as soon as all the tectonic havoc started in the Late Cretaceous. The Colorado Plateau has been uplifted about 3,660 m (12,000 ft) since the end of the Cretaceous about 66 million years ago (Fillmore, 2000). Some of this uplift occurred geologically rapidly.

As the rate of uplift increased, so did the rate of erosion. The Colorado River, for example, carved its present course within the last 6 million years. With uplift, streams throughout the Colorado Plateau began to dissect the topography into the landscape we see today with unprecedented vigor, carving the rocks and carrying away the dismantled strata into the landscape we see today.

Figure 1: Location of Natural Bridges National Monument relative to Colorado Plateau physiographic features. Light gray area signifies the areal extent of the Colorado Plateau. Dark gray and black areas represent uplifts and mountains.

Geologic Issues

A Geologic Resource Evaluation (GRE) workshop was held for National Park Service units in the Southeast Utah Group (SEUG) May 24- 27, 1999, to discuss the geologic resources, to address the status of geologic mapping by the Utah Geological Survey (UGS), and to assess resource management issues and needs. Additionally, June 3- 5, 2002, staff of the National Park Service, Utah Geological Survey, U.S. Geological Survey, Bureau of Land Management, Northern Arizona University, and Brigham Young University participated in a geoindicators scoping meeting in Moab, Utah. The following pages synthesize the results of these meetings to address economic resources, potential geological issues, future scientific research projects, and interpretive needs for Natural Bridges National Monument.

Uranium and Mining Issues

The Paradox Basin has been the site of uranium mining for almost a century. A discovery of a large unoxidized ore deposit on the flank of Lisbon Valley anticline, southeast of the park, kindled public excitement in 1952 (Chenoweth, 1996). The principal host rocks for the radium, vanadium, and uranium deposits exposed at Natural Bridges National Monument is the Triassic Chinle Formation. In the Chinle, gray, poorly sorted, fine- to coarse- grained, calcareous, arkosic, quartz sandstone contains the uranium ore (Chenoweth, 1996).

One principal mining area for uranium was White Canyon although the location of mining activity to Natural Bridges National Monument is not clear in the summary article by Chenoweth (1996). Copper was first discovered in White Canyon in the 1880s, and in 1920, uranium minerals were found to be associated with the copper (Chenoweth, 1996). From 1948- 1951, prospecting was intense in White Canyon and nearby Red Canyon and Deer Flat. During this period prospectors located numerous unpatented mining claims and opened several producing mines.

During the period 1948- 1987, 2,259,822 tons of ore averaging 29% U_3O_8 containing 11,069,032 pounds U_3O_8 were produced from 125 properties in the White Canyon mining district. Ore bodies in the White Canyon mining area are variable in size but are generally closely- spaced, lenticular ore pods that are concordant with bedding. The ore pods range from a few feet to a few hundred feet in length and from less and 0.3 to 4 m (1 to 12 ft) in thickness. They are, on average, five to ten times as long as they are wide. In one mine, the ore is continuous for 2,100 m (7,000 ft). The five largest properties account for 61% of the total uranium produced in the area (Chenoweth, 1993, 1996).

The Mexican Hat unit in Mexican Hat, Utah, processed most of the ore from the White Canyon area until it closed in 1965.

The Atlas Corporation acquired the Mexican Hat mill in July, 1963, and when the mill closed, the ore was shipped to their Moab mill. Atlas closed their mines in the area in 1982.

Abandoned mines pose a serious potential threat to any ecosystem. Even in arid environments, surface water, runoff, and groundwater can be contaminated with high concentrations of heavy metals, leached from the mine tailings. Heavy metals may also contaminate nearby soils which in turn can damage the plant and animal life that live on the soil.

Another threat specific to uranium mining is that of radon gas exposure. Radon is a daughter product of the radioactive decay of uranium. This tasteless, odorless gas is a known carcinogen that usually concentrates in low lying areas like basements and mine shafts.

Inventory, Monitoring, and/or Research Needs

- Conduct periodic water (surface and groundwater) and soil sampling and testing to detect uranium in those resources. Drinking water is especially important to monitor. White Canyon, Red Canyon and Deer Flat are hotspots for uranium contamination.

- Investigate the natural occurrence of uranium- bearing rocks throughout the park including descriptions, uranium content tests, and locations, i.e. where the beds crop out and are accessible to the public, flora and fauna.

- Complete inventory of the uranium content in the recent unconsolidated deposits and soils as well as the uranium bearing stratigraphic units (Chinle Formation).

Slope Failures

The potential for landslide and rockfall exists along all roads and trails at Natural Bridges National Monument. These events cause road problems and closures on a continual basis at the monument. Certain cliff forming units such as the Wingate Formation, the Cedar Mesa Formation and units of the Organ Rock Formation are especially hazardous when undercut by a road or trail.

Similarly, slumps and other forms of slope failure are common for units that are not necessarily associated with cliffs. Rocks rich in mudstone for instance, like the Moenkopi formation are especially vulnerable to failure when exposed on a slope. Precipitation necessary to produce flash flooding at Natural Bridges loosens rock and soil on slopes lacking stabilizing plant and tree roots The rock and soil, suddenly saturated with water, slip down the slope causing a huge slump or mudslide/flow.

Inventory, Monitoring, and/or Research Needs

- Perform a comprehensive study of the erosion/weathering processes active at Natural Bridges National Monument, taking into account rock formations, slope aspects, location and likelihood of instability.
- Create a rockfall susceptibility map using rock unit versus slope aspect in a GIS; use the map in determining future developments and current resource management including trails, buildings, and recreational use areas.

Bridge Collapse

Several years ago, Landscape Arch in Arches National Park collapsed in a few places and was recorded by a tourist. Potential bridge collapse is possible at Natural Bridges National Monument, especially along the span of Owachomo Bridge in Armstrong Canyon which is only 3 m (9 ft) thick at the crest of its span.

Earthquake potential is high along the Moab Fault in nearby Arches National Park, Southeast Utah Group (SEUG). While this and other faults in the Paradox Basin are associated with salt structures, the Colorado Plateau interior does possess a low level of seismic hazard (Wong *et al.*, 1996). Ground shaking from earthquakes may impact the bridges at Natural Bridges National Monument causing catastrophic failure of one or more of the bridges.

Inventory, Monitoring, and/or Research Needs

- Perform engineering studies using a strain meter to assess possible collapse hazards.
- Use high resolution Global Positioning System (GPS) to detect moving, swelling, and collapse in areas of the monument.
- Obtain access to regular seismic activity reports or a seismometer to measure activity in the area.
- Perform a comprehensive, large scale, exhaustive map study of the bridges to determine minute points of weakness and to better understand the structures and their weaknesses.

Swelling Clays

Swelling soils associated with bentonitic shales of the Chinle, Morrison, and Mancos Formations may be a concern to existing and future developments at Natural Bridges National Monument. Bentonite, a clay- rich rock derived from altered volcanic ash deposits is responsible for the road failures at Mesa Verde National Park among others. This clay swells when wet, causing the ground surface to heave and buckle. Any structures, roads, trails, facilities, etc. found on soils with large concentrations of this mineral will be impacted and potentially destroyed.

Inventory, Monitoring, and/or Research Needs

- Use GIS determine where trails, roads and buildings are present on bentonitic units. This method should also be employed to determine high risk areas where future development should be avoided.
- Perform an exhaustive mapping study of where specific bentonitic beds are located in the units listed above (Morrison Formation and Mancos Shale) to allow for more precise hazard assessment.

Noise Pollution

Low flying military jet aircraft often cause sonic booms in areas of low population density, such as that of southern Utah. These events are significant contributors to noise pollution in addition to the threat posed by oil and gas development. Sonic booms are so powerful they pose an additional threat. They can affect geological features. Much like seismic waves, sound waves are transmitted through rock. In an area with delicate suspended geologic features such as those at Natural Bridges National Monument and Arches National Park, any disturbance is a concern to management.

Inventory, Monitoring, and/or Research Needs

- Monitor decibel levels in the monument.
- Contact local industries, military installments, etc. to establish a working relationship with which to help alleviate some of the noise pollution problems.
- Conduct stress studies to determine effects of sound waves on the natural bridges.

Water Issues

The Cedar Mesa Sandstone is the only formation underlying the monument that contains fresh water (Martin, 2000). Salt water fills the pore space in the other formations. Thus, the Cedar Mesa Sandstone is the primary aquifer unit at Natural Bridges National Monument. Aquifer tests were conducted on the two water supply wells for the monument, but data collected during the testing were not precise and thus, not suitable for computation of aquifer parameters: transmissivity, conductivity, or storage coefficient (Martin, 2000). No other wells exist within 8 km (5 mi) of the monument. The lack of wells also inhibits any determination of groundwater flow direction.

Water quality data indicate that the water quality in the Cedar Mesa aquifer is excellent. This unit is also open to the surface and therefore is extremely susceptible to contamination. Contamination of the aquifer is especially possible from fuel tanks, from sewer lines and the sewage lagoon, and from products stored in the maintenance shop at the park. Another source of contamination is the effluent resulting from livestock that graze in or near the monument (incomplete fencing). This type of contamination impacts springs, seeps, and streams in nearby Arches National Park.

Regarding water quality, a *Drinking Water Source Protection Plan* for Natural Bridges National Monument prepared by the Water Resources Division found few potential contaminants in the park (Martin, 2000). A list of possible potential contaminant sources include: 1) diesel fuel that may leak from a buried, 3,000- gallon storage tank, and 2) sewage that may seep into the aquifer from a broken sewage line that leads to the sewage lagoons, 3) solvents, degreasers, oil, and paint that are stored in small quantities in maintenance. As these potential contaminants are stored on concrete floors that would provide short- term containment until a spill could be cleaned up, the potential for water contamination from these sources is low., like the Moenkopi formation are especially vulnerable to failure when exposed on a slope.

Inventory, Monitoring, and/or Research Needs

- Conduct hydrogeologic studies to define subsurface flow patterns, regional and local flow systems, and the conductivity and transmissivity of the Cedar Mesa Sandstone.
- Monitor water quality at multiple sample locations within the monument, drinking water sources are especially important. Special attention should be paid to the high risk areas noted above.
- Install further wells for testing and drinking water.
- Investigate the impacts of copper and uranium mining and oil and gas development on park resources.
- Identify and study potential sources for groundwater quality impacts in parks, including those listed above.
- Install transducers and dataloggers in wells.
- Investigate additional methods to characterize groundwater recharge areas and flow directions.

Streamflow, Channel Morphology and Sediment Load

Surface water drains from Natural Bridges National Monument by the rivers that flow through White Canyon and Armstrong Canyon and their tributaries. In the arid climate of southern Utah, intense, short duration, seasonal rainstorms and subsequent flash floods impact channel morphology and the creation/destruction of bridges. These intense seasonal events may periodically deposit thick layers of sediments. Sediment loads and distribution affect aquatic and riparian ecosystems, and can result in changes to channel morphology and overbank flooding frequency. The canyons are also discharge points for local groundwater flow (Martin, 2000). The deep canyons dissect the region into a discontinuous series of plateaus and canyons and disrupt local groundwater flow. If recharge is sufficient, the plateaus may contain local groundwater systems that discharge as springs in the canyons.

Inventory, Monitoring, and/or Research Needs

- Monitor seasonal spring locations with regards to their location, water quality, and maximum flow.
- Perform channel morphology studies, with regards to intense seasonal flashfloods. Consult professional geomorphologists with regards to erosional processes.
- Inventory current channel morphological characteristics.
- Monitor changes in morphology, especially in areas surrounding the natural bridges.
- Conduct hydrologic condition assessment to identify actual and potential "problem reaches" for prioritized monitoring.
- Monitor identified "problem reaches" with repeat aerial photography.
- Research effects of land use and climatic variation on streamflow.
- Investigate paleoflood hydrology.
- Gage stream sediment storage and load. There are no data available except on the main stem of the Colorado River at Cisco, Utah, and the Green River at Green River, Utah.
- Measure sediment load on streams of high interest for comparative assessment.

Desert Surface Crusts (biological and physiochemical) and Desert Pavements

Biological soil crusts composed of varying proportions of cyanobacteria, lichens, and mosses are important and widespread components of terrestrial ecosystems in all four parks, and greatly benefit soil quality and ecosystem function. These plants increase water infiltration in some soil types, stabilize soils, fix atmospheric nitrogen for vascular plants, provide carbon to the interspaces between vegetation, secrete metals that stimulate plant growth, capture nutrient- carrying dust, and increase soil temperatures by decreasing surface albedo. They directly affect vegetation structure due to effects on soil stability, seedbed characteristics, and safe- site availability, and indirectly through effects on soil temperature and on water and nutrient availability. Decreases in the abundance of biological soil crusts relative to physicochemical crusts can indicate increased susceptibility of soils to erosion and decreased functioning of other ecosystem processes associated with biological crusts. Physiochemical crusts can protect soils from wind erosion but not water erosion, and do not perform other ecological functions of biological crusts

Inventory, Monitoring, and/or Research Needs

- Inventory condition and distribution of biological soil crusts.
- Investigate connection between ecosystem function and biological crusts.
- Map crust communities in relation to environmental factors.
- Study crust recovery rates and susceptibility to change.
- Study crust population dynamics and conditions.

Wind Erosion and Deposition

In addition to water, wind is a major force that can redistribute soil and soil resources (e.g., litter, organic matter, and nutrients) within and among ecosystems. Erosion and deposition by wind is important in all four parks and can be accelerated by human activities. Accelerated losses of soil and soil resources by erosion can indicate degradation of arid- land ecosystems because ecosystem health is dependent on the retention of these resources. In addition, wind erosion and sediment transport may be strongly impacted by land- use practices outside the parks. Eolian sand from disturbed surfaces may saltate onto undisturbed ground, burying and killing vegetation and/or biological soil crusts, or breaking biological soil crusts to expose more soil to erosion. Because park management practices limit or prohibit off- road travel, human impacts within the parks primarily are associated with off- trail hiking in high- use areas. Where livestock grazing or trailing is still permitted (e.g., CARE), accelerated soil erosion can be more extensive.

Inventory, Monitoring, and/or Research Needs

- Monitor movement of soil materials.
- Investigate ecosystem consequences of movement
- Investigate natural range of variability of soil movement in relation to landscape configuration and characteristics.

General Geology

The unique geology of Natural Bridges National Monument lends itself to potential scientific research projects that address the Paleozoic and Mesozoic stratigraphy, the regional and local hydrology, and weathering/erosion rates.

Inventory, Monitoring, and/or Research Needs

- Perform rock color studies.
- Identify unconformity- bounded stratigraphic packages in order to better define the depositional systems present in the past.
- Develop more graphics and brochures emphasizing geology, targeting the average enthusiast.
- Hire a full- time geologist to handle geologic issues for the SEUG.

Oil & Gas Issues

The combination of salt, organic- rich shale, porous limestone and sandstone, pressure and time has resulted in large accumulations of oil and gas in the Paradox Basin. Since the discovery of the giant Aneth Field in 1956, the Paradox Basin has been a prolific producer of oil and gas (Baars *et al.*, 1988). The oil fields in southeastern Utah lie east of the Monument Upwarp (Harr, 1996). Natural Bridges National Monument is located near the crest of the Monument Upwarp, which is not prospective target for oil and gas exploration. Tertiary, Cretaceous, Jurassic, Triassic, and uppermost Permian strata have been stripped by erosion from the upwarp. The Monument Upwarp is a “breached” anticline, and any oil and gas that may have migrated into Pennsylvanian and younger reservoirs have already escaped to the surface either through direct exposure or through fractures (Nuccio and Condon, 1996).

At present there are no known oil and gas resources in the monument. However, development of these resources outside the monument could have a significant impact on the ecosystem and viewshed of the monument. Oil and gas development activities include: seismic exploration, construction of roads for drill pads, well drilling and completion, and production activities, such as construction and operation of pipe lines, separation facilities, storage tanks, etc.

Impacts include: noise, vibration and dust; scars from roads and drill pads; oil spills; escape of natural gas, carbon dioxide and hydrogen sulfide; light pollution from drill rigs and production facilities; surface and groundwater contamination by drilling fluids and water disposal; and pollution from abandoned equipment, trash and human wastes.

Inventory, Monitoring, and/or Research Needs

- Monitor oil and gas activity in the vicinity of the monument.
- Acquire plugging records of oil and gas wells potentially connected to park groundwater systems.

Air Issues

Harmful chemicals and particulates are responsible for increased acid deposition in southern Utah. Sources of these contaminants include the Navajo Power Plant, the Four Corners Plant, the Emery Plant and the Huntington Plant.

Acid rain can dramatically affect the geologic landscape by preferentially eroding and weathering carbonate layers, intergranular cements and entire rock units. This preferential erosion, accelerated by the increasing acidity of precipitation, can destabilize slopes and cliffs resulting in a greater frequency of rock falls and slope failure.

Inventory, Monitoring, and/or Research Needs

- Monitor rainwater pH, noting spikes or changes.
- Establish a working relationship with the appropriate industries in an attempt to decrease the level of pollutants in the area over the monument.

Geologic Features and Processes

Natural Bridge Formation

The three bridges in Natural Bridges National Monument, Sipapu, Kachina, and Owachomo, are among the ten largest in the world, and they are all developed in the Lower Permian Cedar Mesa Sandstone. Hopi names were assigned to the bridges because modern- day Hopis are descendents of the people who occupied these remote canyons in ancient times (Huntoon *et al.*, 2000). Sipapu means "the place of emergence," an entryway through which the Hopi believe their ancestors came into this world. Kachina Bridge is named for the rock art symbols on the bridge that resemble symbols commonly used on Kachina dolls. Owachomo means, "rock mound," and was named in honor of a feature atop the bridge's east abutment (Huntoon *et al.*, 2000). Although the Cedar Mesa Sandstone was deposited about 270 Ma, the bridges are likely less than 30,000 years old (Huntoon *et al.*, 2000).

When Eocene meandering rivers cut into the resistant Cedar Mesa Sandstone, the meandering patterns established in the overlying, non- resistant rocks were superimposed on the resistant sandstone. Because these rivers drained into the Colorado River and the Colorado River flowed to the sea, the Colorado River controlled the rate and degree of incision of these tributary streams. Until about 6 Ma, the Colorado River was about 1 km (0.6 mi) higher than it is today. There was no Grand Canyon. Then, for reasons related to tectonics (i.e., rearrangement of lithospheric plates) or climate or both, the *baselevel* (see glossary) of the Colorado River dropped. As the Colorado River began to cut the Grand Canyon, local baselevel for rivers throughout southeastern Utah also dropped. Rapid incision followed for all rivers that drained into the Colorado River. Vertical incision was more rapid than lateral erosion so that the rivers' channels entrenched into the underlying bedrock, preserving their meandering channel patterns (Huntoon *et al.*, 2000).

The last ice age profoundly effected the formation of the natural bridges. During the Pleistocene Epoch of the Quaternary Period, the climate of Utah was wetter. Large floods were probably common in the wetter glacial period of the Pinedale Glacial, a period that lasted from about 30,000 to 12,000 years before present. Consistent with river dynamics, the cut- bank, or outer sides of the meander loops would erode until only thin canyon walls would separate one cut- bank from the next on the meander loop. Eventually, the river penetrates the canyon wall, shortens its course, and abandons the meander loop. The bridges in White Canyon and Armstrong Canyon are the remnants of thin canyon walls that were penetrated by the floods (Huntoon *et al.*, 2000).

Sipapu Bridge

At 67 m (220 ft) high and a span of 82 m (268 ft), Sipapu Bridge is the largest bridge in Natural Bridges National Monument and is second in size only to Rainbow Bridge located in Rainbow Bridge National Monument over Bridge Creek near Lake Powell (Huntoon *et al.*, 2000). Sipapu is considered to be a "mature" bridge. Abutments that lie above the level of the present- day streambed edge the symmetrical shape with a smooth, rounded opening.

The bridge developed when the stream in White Canyon cut off a meander bend (figure 2). The abandoned meander is visible from the Sipapu Bridge Trail.

Kachina Bridge

Kachina Bridge is a massive, youthful bridge that is still growing in size. Located near the confluence of White and Armstrong Canyons, Kachina is 64 m (210 ft) high with a span of 62 m (204 ft) (Huntoon *et al.*, 2000). The sandstone making up the span is 28 m (93 ft) thick. In a dramatic display of the impermanence of landforms, an estimated 4,000 tons (3.6×10^6 kg) of sandstone sloughed off the underside of the bridge on its west abutment in June 1992. Kachina Bridge formed when the stream in White Canyon broke through a thin canyon wall just upstream of its original junction with Armstrong Canyon (figure 3) (Huntoon *et al.*, 2000

Owachomo Bridge

The oldest bridge in Natural Bridges National Monument is Owachomo Bridge, which is nearing collapse in Armstrong Canyon. Standing 32 m (106 ft) high with a span of 55 m (180 ft), Owachomo is only 3 m (9 ft) thick at the crest of its span. The bridge lies above and parallel to the present- day streambed.

Owachomo Bridge formed when a stream in Tuwa Canyon eroded into Armstrong Canyon. The Tuwa stream twice cut through meander bends into Armstrong Canyon. A second cutting event resulted in abandonment of the part of Tuwa Canyon that passed under the bridge so that Owachomo Bridge is now isolated from the main channel (figure 4).

Stream Channel Morphology Change

Streams, especially in flash flood situations, are dynamic and can produce rapid changes in landforms. These landforms include channel shape, bedforms, stream banks, bar deposits, terraces and meander bends.
The extreme channel sinuosity at Natural Bridges played a major role in creating the bridges and continues to have an effect on the landscape today.

Future bridges are in the process of being formed in White, Armstrong, and Tuwa Canyons. Channel dimensions and patterns are affected by changes in flow rate and sediment discharge, as well as the ratio of suspended sediment to bed load. These parameters are all pushed to extremes during the flash floods inherent to the desert landscape in southern Utah.

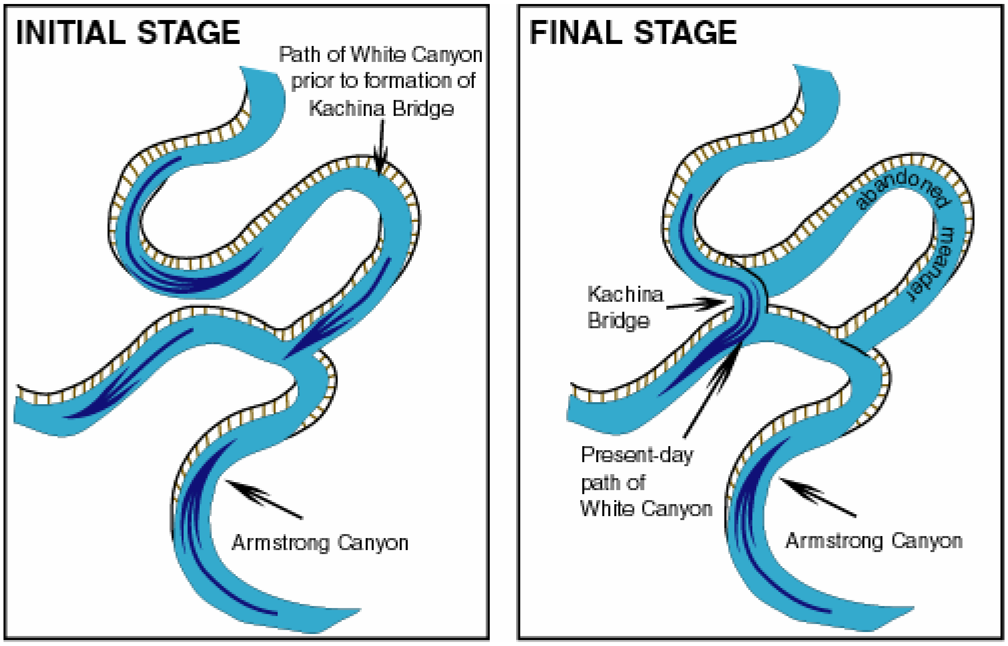


Figure 2: Interpreted evolution of the initial and final states of Sipapu Bridge. Initial stage corresponds to a time prior to bridge formation. Final stage corresponds to present-day conditions. From Huntoon and others (2000).

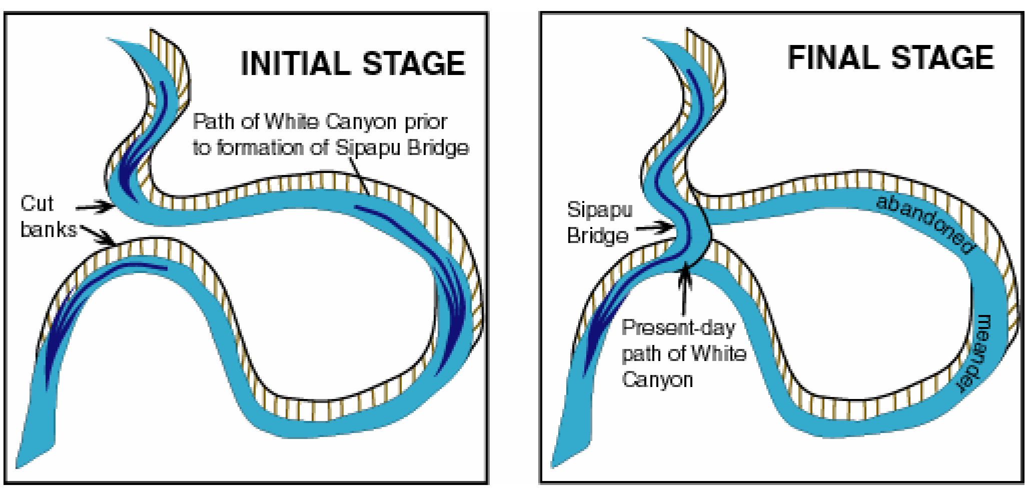


Figure 3: Interpreted evolution of the initial stage to final stage of Kachina Bridge development. Initial stage corresponds to a time prior to bridge formation. Final stage corresponds to present-day conditions. From Huntoon and others (2000).

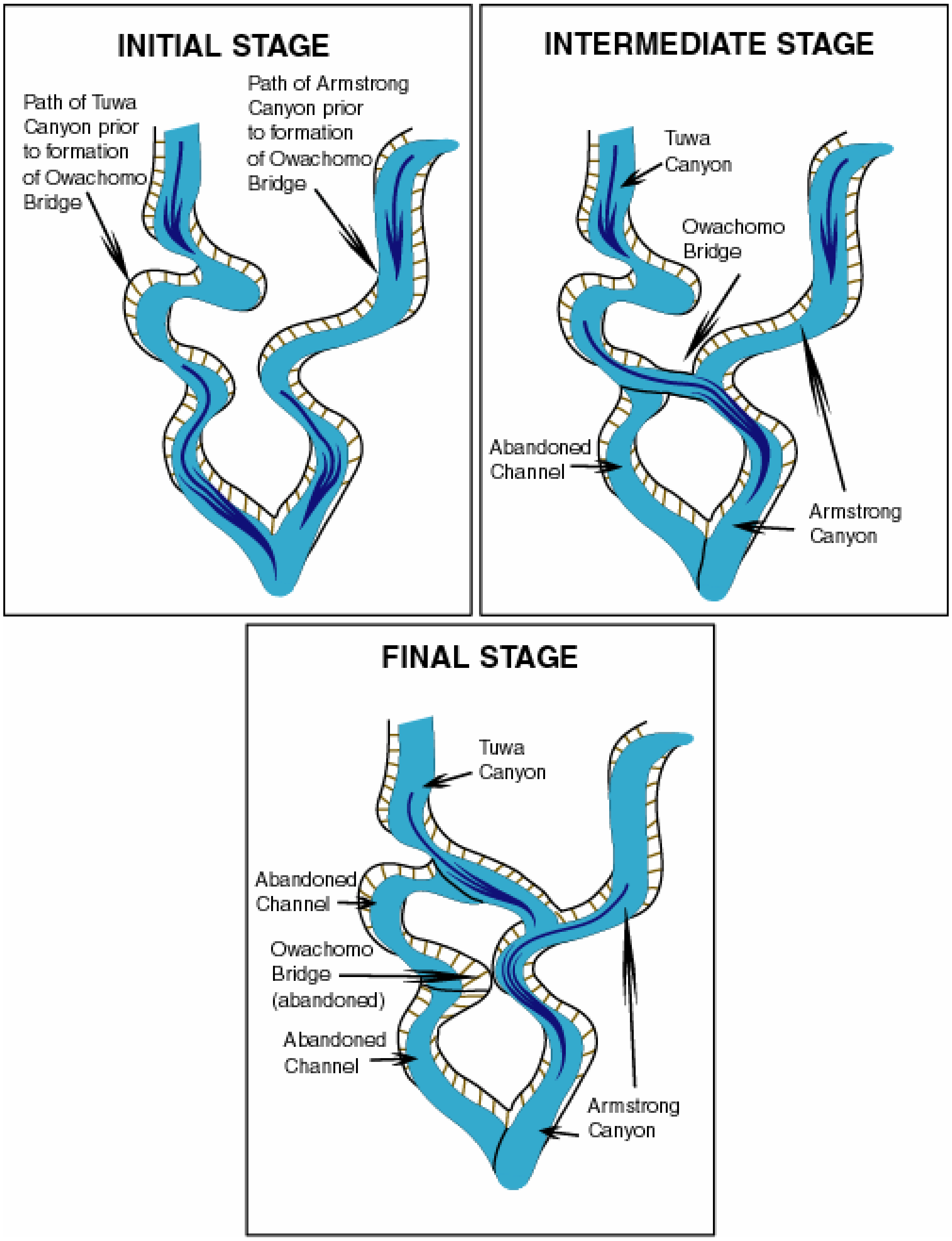


Figure 4: Interpreted evolution of Owachomo Bridge. The initial stage corresponds to the time prior to bridge formation and the final stage is present-day condition. From Huntoon and others (2000).

Formation Properties

This section serves as a critical link between resource managers and the digital geologic map of the park. Formation Tables are highly generalized and are provided for informational purposes only. Ground disturbing activities should not be permitted or denied on the basis of information contained in these tables. More detailed unit descriptions can be found in the help files accompanying the digital geologic map or by contacting the Geologic Resources Division.

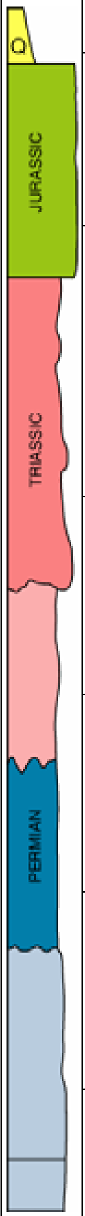
Natural Bridges National Monument is underlain almost entirely by Lower Permian, clastic sedimentary rocks. Triassic and Jurassic rocks that overlie the Permian strata are exposed along the surrounding skyline that is visible from Natural Bridges National Monument and include the Lower Triassic Moenkopi Formation, the Upper Triassic Chinle Formation, and the Lower Jurassic Wingate Sandstone (Huntoon *et al.*, 2000).

The Organ Rock Formation, the Cedar Mesa Sandstone, and the lower Cutler beds are part of the Cutler Group. While a geologic "formation" is a mappable unit, distinct from overlying and underlying units, with recognizable upper and lower boundaries, a stratigraphic "group" consists of two or more formations that are distinct, yet lithologically similar. The informal, lower Cutler strata are the oldest Permian rocks exposed on Cedar Mesa.

Toward the north and northeast, the Cutler Group grades into the coarser- grained rocks of the Cutler Formation. Because the Cutler Formation consists of a heterogeneous mixture of sandstones and conglomerates that were deposited in fluvial and alluvial fan environments adjacent to the Uncompahgre uplift, the formation has not been subdivided into individual units as in the Cutler Group.

The following page presents a table view of the stratigraphic column and an itemized list of features per rock unit. This sheet includes several properties specific to each unit present in the stratigraphic column including: map symbol, name, description, resistance to erosion, suitability for development, hazards, potential paleontologic resources, cultural and mineral resources, potential karst issues, recreational use potential, and global significance.

Formation Properties Table



Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Development	Hazards	Potential Paleontologic Resources	Potential Cultural Resources	Mineral Specimens	Mineral Resources	Habitat	Recreation Potential	Global Significance
	Alluvium (Qal)	Sand, gravel, clay, and other river derived sediments; little study done in NABR area on recent sediments	Low	Unconsolidated, unsuitable for foundation material for buildings; campgrounds possible	Slide and slump potential in unconsolidated unit	Recent fauna and flora, packrat middens, dung pellets, extinct mountain goat fossils, spruce, limber pine and Douglas fir microfossils	Dwellings and artifacts possible	None documented	Gravel, sand, clay	Habitat for animals and plants	Good for most recreation	Unknown
	Wingate Sandstone (Jw)	Cliffs average 100-130 m (300 to 400 ft) thick; reddish-orange sandstone with massive eolian cross-beds; quartz grains frosted; fine-grained with some feldspar and traces of chert and other accessory minerals	Very high	Suitable for most development except where highly fractured; commonly present as cliff forming member thus care should be taken when building roads below it or trails near rim	Rockfall potential extreme; normally exposed in undercut cliffs; trails should not be developed near cliffs	None documented	Cliff faces may expose petroglyphs and unit is often undercut providing potential caves for dwelling	Frosted quartz grains	Attractive flagstone and building material	Cliff faces provide ledges and undercut areas provide caves for bird and animal habitat	Very attractive for climbers and mountain bikers; Suitable for most recreation unless at the base of a cliff	Records widespread sand seas, or ergs, present during the Jurassic
	Chinle Formation (TRc)	100 to 200 m (300 to 600 ft) thick; Shinarump pebble conglomerate dominates lower beds - pebbles of quartz, quartzite, chert as well as uranium deposits; overlying members are a mixture of gray, red, pink, orange, and purple mudstone, sandstone and conglomerate interbeds with some limestone locally present	Moderate to high	Lower conglomeratic beds are suitable for most development unless highly fractured; upper beds (majority of unit) can be unstable along slopes especially where significant mudstone is present; mudstone can pose a problem with road development if clay content (especially bentonite) is high.	Slide and slump potential in mud-rich layers; rockfall hazard high for lower beds if undercut or exposed on a cliff face	Burrow and root casts as well as paleosols found locally; petrified wood	Petrified wood and varicolored rocks may have interested ancient Native Americans	Uranium-rich beds	Significant uranium deposits in Shinarump conglomerate; attractive flagstone material	Plucked pebbles in conglomerate provide holes for nests of birds and other small animals	Conglomeratic lower beds attractive for climbers, bentonitic and mud-rich layers should be avoided for trail development, susceptible to failure when wet	Widespread unit of Triassic age; significant deposits of uranium and petrified wood
	Moenkopi Formation (TRm)	100 to 130 m (300 to 400 ft) thick; lower beds of coarse-grained sandstone, interbedded with chert pebble conglomerate, grayish-red, pale reddish-brown to yellowish-gray sandstone and sandy siltstone; features include ripple marks, cross laminations, and wavy bedding; limestones, gypsum beds, and bentonites are locally present	Low to moderate	High variability of unit renders it unstable along slopes; bentonitic clay shrinks and swells making road construction and trail development problematic on this unit	Slide and slump potential in mud-rich (especially bentonitic) bands; rockfall hazard if sandstone beds form low cliffs	Fossils of plants and animals present locally	Unknown	Gypsum crystals and layers	Gypsum; high concentrations of hydrocarbon rich rocks	Banded unit creates ledges and hollows attractive for birds and small animals for sheltered habitat	Poor for trails and most recreational uses due to susceptibility to slope failure	Records monsoonal wet-dry climate during Triassic time
	Organ Rock Formation (Po)	Averages about 100 m (300 ft) thick; reddish-brown to light red, feldspar rich, very fine- to fine-grained sandstone, siltstone, mudstone and minor carbonate-pebble conglomerate interbeds; appears banded due to alternating resistant and nonresistant beds; features include sand-filled desiccation cracks, and burrows as well as ripples and some crossbeds	Low to moderate	Banded nature of unit makes it relatively unstable where a slope is present; otherwise, unit is suitable for most development	Slide and slump potential in mud-rich bands; rockfall hazard if sandstone beds form low cliffs	Some root casts and petrified soil horizons found west of NABR; ferns, pteriodosperms, and conifer fossils, fish, amphibians and reptile fossils	Unknown	None documented	None documented	Banded unit creates ledges and hollows attractive for birds and small animals for sheltered habitat	Good for most uses, especially trails and mountain biking	Unit records increasingly arid conditions in the late Permian time
	Cedar Mesa Sandstone (Pc)	Unit averages 300 m (1000 ft) thick in NABR area; two distinct facies, the white sandstone facies and the red mudstone facies are present in monument; the first facies is composed of fine-grained sandstone with large scale eolian crossbeds; the second facies consists of horizontally laminated beds of red micaceous mudstone interbedded with fine-grained sandstone and some limestone beds locally	High	Suitable for most development unless highly fractured which may make waste facility development problematic; interbedded mudstones may compromise stability on slopes, thus buildings on slopes should avoid these layers	Rockfall potential high on cliff faces; slide potential in the mudstone-rich layers	Small marine fossils, conifer logs, reptile bones and teeth, plant stems and fern leaves, burrows and root casts	Cliff faces may expose petroglyphs, concretions in limestone layers may have provided tool material	Rhizoliths (large root casts)	Attractive flagstone material	Vugs in limestone may provide nesting habitat especially where exposed on cliffs	Good for most uses, attractive to rock climbers, trail development should avoid mudstone rich layers exposed on slopes	Evidence of large Permian age aeolian fields
	Lower Cutler Beds	Informal unit exposed near NABR, 122-152 m (400-500 ft) thick of arkose, dark red, orange and pinkish to light greenish-gray quartz sandstone, mudstone and limestone interbeds Grain size varies from fine to coarse with abundant crossbeds; some conglomerates exposed east of NABR	Moderate	Suitable for most development except where highly fractured, in which case waste facilities should not be developed	Slide potential where thin-bedded and shale rich	Fusulinids; some petrified wood, & vertebrate footprints	Chert present as nodules in limestone may have been used for tools	None documented	Attractive flagstone material	Vugs in limestone may provide nesting and den cavities	Good for most uses, especially trails, not a good climbing material	Pennsylvanian and Permian fusulinids

Geologic History

Natural Bridges National Monument, Utah's first national monument, was established to protect three large natural bridges and ancient masonry structures constructed by ancestral Puebloan people. Unlike an arch, like those at Arches National Park, a natural bridge forms through the process of flowing water. The landscape of the monument stands as an elegant testimony to the power and splendor of geologic processes and the dynamic change that operate throughout geologic time (see Appendix 6). Although carved into Permian age Cedar Mesa Sandstone that was deposited about 270 million years ago, the bridges are probably less than 30,000 years old.

Being part of the geological region known as the Colorado Plateau, the strata in the Monument region record the growth of the North American continent. In the continent's infancy, an ocean bordered the Colorado Plateau. As land accreted to the western margin of the North American continent during the Paleozoic era, the region became part of a Western Interior Basin. Towards the end of the Paleozoic, as the crustal landmasses on the globe sutured together into one big supercontinent, Pangaea, the ancestral Rocky Mountains were uplifted and supplied sediment to the Natural Bridges area.

The Uncompahgre Uplift was part of the Ancestral Rocky Mountains that formed as the last land masses sutured together to form the supercontinent, Pangaea, beginning in the Pennsylvanian Period. South America collided with the southern part of North America near Texas and Oklahoma, generating the Ouachita Orogeny. The Marathon- Ouachita- southern Appalachian mountain chain resulted from this collision. The effects were felt in the interior of the continent, as well, where jagged peaks split the skyline as the Ancestral Rocky Mountains were thrust from the plain. Two principal mountain ranges formed along northwest- southeast trending high- angle reverse faults: the Uncompahgre and Front Range uplifts (figure 6).

Boulder conglomerates eroded from the fault- bounded Uncompahgre Highlands were deposited in the Paradox Basin and eventually became the Cutler Formation. Like today in the southwestern desert of the United States, Pennsylvanian – Permian age rivers flowing from the canyons cut in the Uncompahgre Mountains lost their momentum when they debouched from the mouth of the canyon onto the plain, and the coarse material was distributed in fan- shaped deposits called *alluvial fans*. The sediments became progressively finer- grained away from the fault so that feldspar- rich sandstone and silty sandstones were deposited in the distal portions of the fan. Fluvial systems transported sediment throughout the Paradox Basin.

Isopach (thickness) maps showing the thickness of the Cutler Group or Formation and the lower Cutler beds illustrate the effect of the Uncompahgre Highland on the depositional patterns in the Paradox Basin during Pennsylvanian time (Condon, 1997). Within 40 km (25 mi) of the fault that defines the southwestern border of the Uncompahgre Highland, over 2000 m (6500 ft) of Cutler Group or Formation was deposited in a trough that parallels the mountain front. A similar pattern is found in the lower Cutler beds although the trough is not as well defined. Rather, the lower Cutler beds form three, fan- shaped deposits over 300 m (1000 ft) thick next to the Uncompahgre front (Condon, 1997). The Monument Upwarp doesn't appear to have influenced the depositional patterns, and thus, the upwarp had not yet developed.

The Monument Upwarp formed on the southwestern edge of the Paradox basin during the Early Permian, however, and contributed sediments to the basin possibly into the Early Triassic (Huntoon *et al.*, 2000). Extending from Monument Valley to about the confluence of the Green and Colorado Rivers, the Monument Upwarp was a broad, elongate, topographic high during the Early Permian (figure 7). Blakey (1996) refers to the upwarp as the Monument "Bench", suggesting a subtle feature in the Permian with subdued relief compared to the Uncompahgre Highlands.

Natural Bridges National Monument lies near the crest of the Monument Upwarp, a broad, structural feature called the Monument Upwarp that extends from southern Utah into northern Arizona, so that the Lower Permian Cedar Mesa Sandstone and Organ Rock Formation are relatively flat- lying strata with only a gentle dip to the southwest. During the Early Permian Period, three major paleotectonic elements influenced deposition in southeastern Utah (Huntoon *et al.*, 2000). The Uncompahgre Mountains lie to the northeast (figure 6). The Monument Upwarp was a north- south trending, positive feature crossing the Arizona/Utah border, and the Paradox Basin lay between the two highlands. Following burial and lithification, the Permian strata were deformed and molded into the present landscape by the Late Cretaceous Period to Tertiary Period Laramide Orogeny and subsequent Cenozoic uplift.

Bordered by the Monument Upwarp and the Uncompahgre Highland, the Cedar Mesa Sandstone thins from the northwest, where it is over 365 m (1200 ft) thick, to the southeast, where it is about 122 m (400 ft) thick (Condon, 1997). Facies changes in the Cedar Mesa Sandstone seem to follow this thickness trend.

To the northwest, the Cedar Mesa is a thick sequence of cross- bedded sandstone, but southeast of the Monument Upwarp, the formation thins and becomes dominated by fine- grained sandstone, mudstone, and evaporite deposits (Blakey, 1996; Condon, 1997).

Depositional trends and isopach maps further document the effect of the Monument Upwarp on the Organ Rock Formation (Stanesco *et al.*, 2000). In the Lower Permian, the upward diverted fluvial channels in the Organ Rock to the northwest. Eolian deposits onlapped the structure from the west and thinned over the crest of the upwarp. During the Lower Permian, Natural Bridges National Monument was on the southeastern edge of the Monument so that the Organ Rock facies are different from those on the northwestern margin of the structure (Stanesco *et al.*, 2000).

Permian Period strata, including the Cedar Mesa Sandstone, were deposited along the western margin of North America in a variety of terrestrial and marine environments. As the Mesozoic dawned, these nearshore to marine environments changed as winds blew across the region, pushing sand into great dune fields that surpass today's Sahara Desert. These dunes and other later deposits buried the Permian strata to a depth of 1,500- 3,000 m (5,000 to 10,000 ft). Now exposed at the surface, the Cedar Mesa Sandstone, the dominant formation in Natural Bridges National Monument, is surrounded by the younger Triassic Period Moenkopi and Chinle Formations and the Jurassic Period Wingate Sandstone.

The rocks exposed at the surface today are the result of a complex relationship between tectonics and sedimentation rates. As Pangaea began to break apart and the landmasses began to drift to their present positions, the climate affecting Natural Bridges became more humid. Sand dunes transformed into river systems, swamps, beaches, and broad level plains. Dinosaurs roamed the region, and periodically, ash drifted into the area from volcanoes far to the west. Rippling effects of lithospheric plate collisions on the western margin of North America caused the Western Interior of North America to be flexed into a shallow basin in the Cretaceous. This Western Interior Basin was flooded by seawater from the Arctic region and from the ancestral Gulf of Mexico as Africa and South America rifted away from North America.

By Late Cretaceous time, about 97 million years ago, the Western Interior Seaway had drowned the previously continental deposits and the Natural Bridges region was an ocean basin, collecting fine- grained sediments that drifted far from the shoreline to the west and southwest. Oscillations in the shoreline, either from increased sedimentation coming off the highlands to the west or from tectonic response to collisions on the western continental margin, caused the shoreline to prograde and recede several times during the next 13 million years. Thick sequences of shale, siltstone, and thin limestone beds accumulated on the margin.

As the Cretaceous Period came to a close, compressive forces outside the borders of the Colorado Plateau, an extensive physiographic province covering parts of Utah, Colorado, New Mexico, and Arizona, caused the region to bow upward as a relatively coherent unit during the Late Cretaceous to Mid- Tertiary Laramide Orogeny. The Monument Upwarp was a minor topographic feature in the late Paleozoic, but formed a broad, north-south trending, regional anticline during the Laramide Orogeny in late Cretaceous to Tertiary time. Erosion stripped the Tertiary and Mesozoic strata from the area of Natural Bridges and left the older Cedar Mesa Sandstone exposed at the surface. Most of the erosion occurred during the last 6 million years when the Colorado Plateau began to rise. The sea retreated from the continent and horizontal forces thrust the Rocky Mountains skyward. As the plateau rose, the Colorado River and its tributaries cut down through the relatively soft sedimentary rocks and effectively entrenched their meandering patterns into the underlying bedrock.

River channels incised into the underlying sediments and filled with Tertiary gravels. Violent volcanic eruptions soon followed as the San Juan Mountains exploded in the mid- Tertiary. Extensional tectonics resulted in the opening of the Rio Grande Rift near the southeast margin of the Colorado Plateau. As the mountains rose, the processes of weathering and erosion began to bevel the mountain front into a relatively flat landscape (*peneplain*) gently sloping to the southwest. A combination of glaciation, increased runoff, a rising Colorado Plateau, and a subsequent lowering of the Colorado River's baselevel, the carved the present- day topography.

During the Pleistocene Epoch of the Quaternary Period (1.64 million – 10,000 years before present) the climate of southeastern Utah was wetter and cooler and runoff from nearby glaciers caused massive, catastrophic flooding in the canyons. The hydraulic force of the rivers, coupled with other erosion processes such as frost wedging, root growth, and groundwater seepage, caused the canyon walls to thin on the upstream and downstream portions of the meander loops.

Today, chunks of canyon walls spall off during flash floods as swirling, turbulent water pounds both sides of the narrow necks, making them even thinner, and this process probably occurred in the Pleistocene, as well. Percolation of water through the wall during times of low water would have weakened the base of the cliff even more. When the canyon walls were breached, natural bridges formed. Three large natural bridges, Sipapu Bridge, Kachina Bridge, and Owachomo Bridge, formed within White and Armstrong canyons in the Monument. These bridges are among the ten largest natural bridges in the world.

The stratigraphic relationships, hydrology, and tectonics offer research projects that might benefit the park. They also create some potential geological issues that need to be addressed.

Large oil and gas fields have been developed in southeastern Utah as have uranium mines that may all pose potential environmental impacts to the Monument region. The effects of alternative energy development have not been addressed for the area. The bridges of Natural Bridges National Monument stand as monuments to the grand expression of *deep time*, that time that surpasses our understanding but reminds us that Earth is not static but is subject to change.

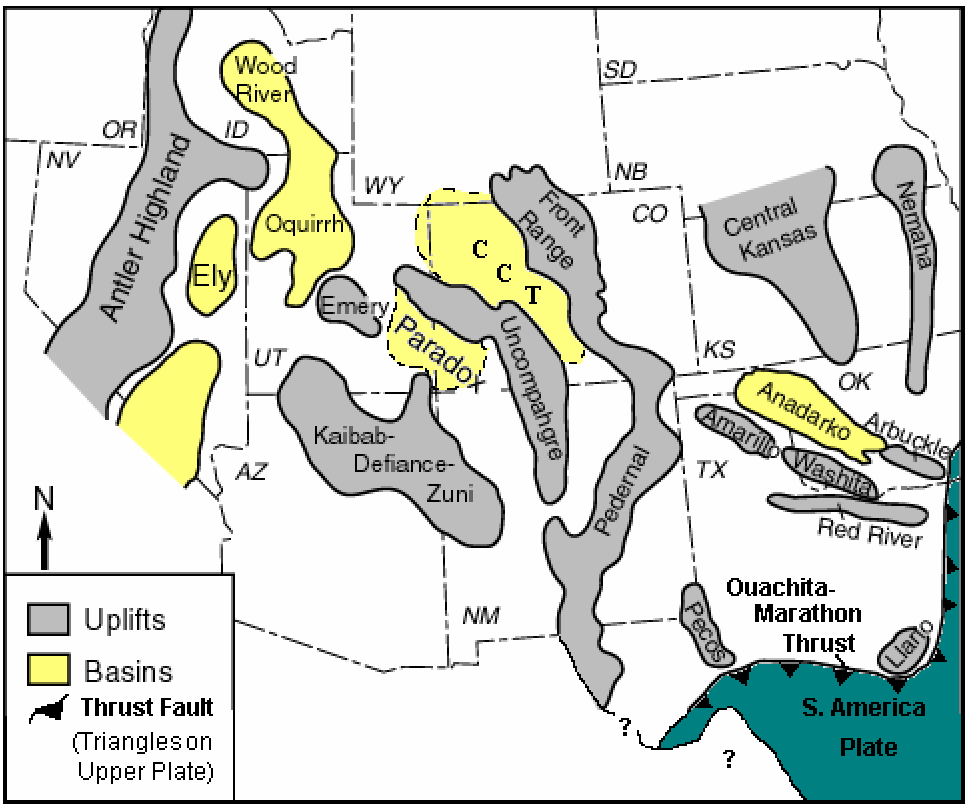


Figure 5: Major uplifts and basins present during the Pennsylvanian age in the southwestern United States. Sediment eroded from the uplifts was deposited in the adjacent basins. Modified from Rigby, (1977).

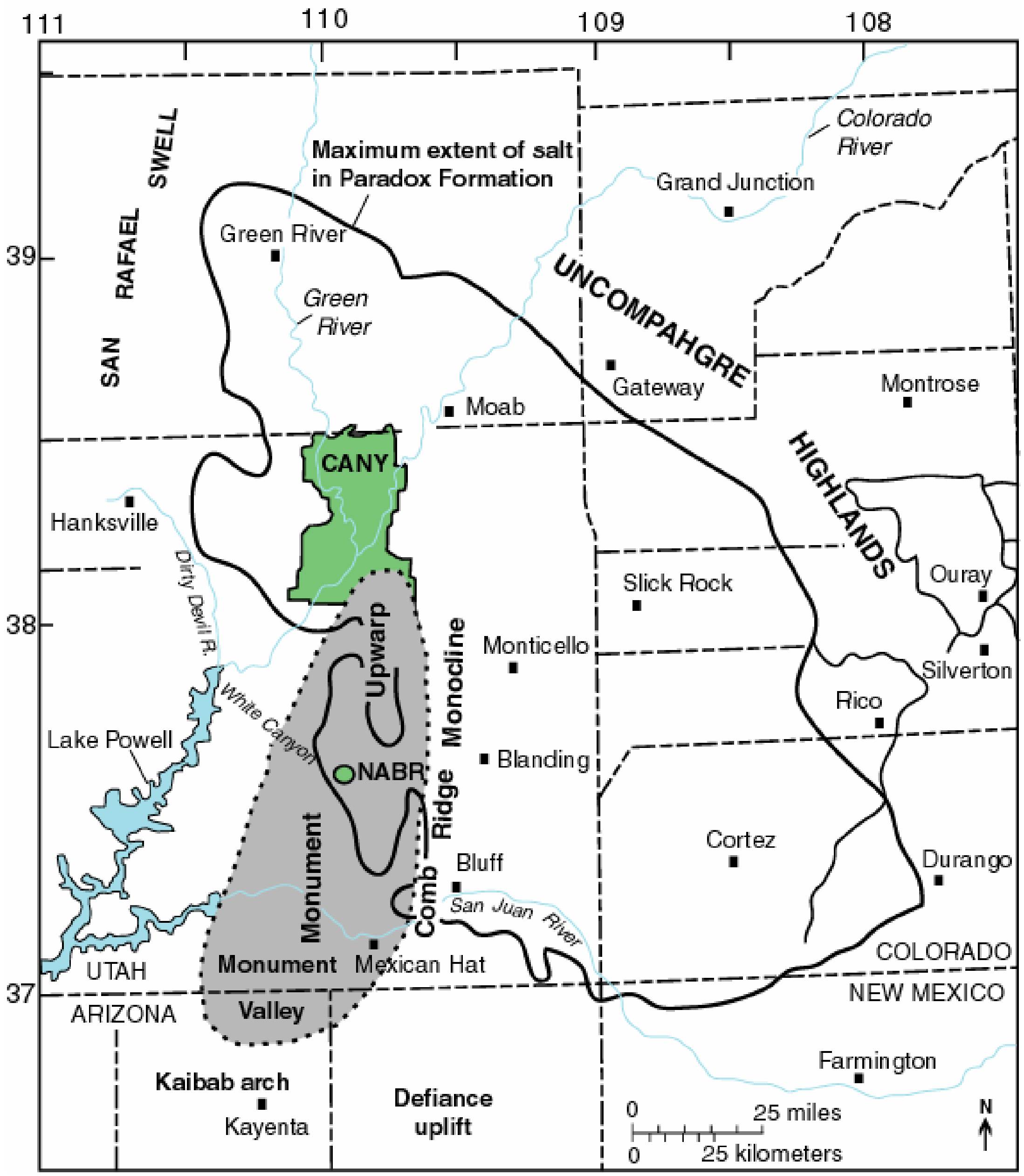


Figure 6: Map showing the geographic features in the Four-Corners region of Colorado, Utah, New Mexico, and Arizona. Shaded area is the Monument Upwarp. Dark outline is the maximum extent of Pennsylvanian-age Paradox Formation salt in the Paradox Basin. NABR: Natural Bridges National Monument. CANY: Canyonlands National Park. Modified from Stanesco *et al.*, 2000.

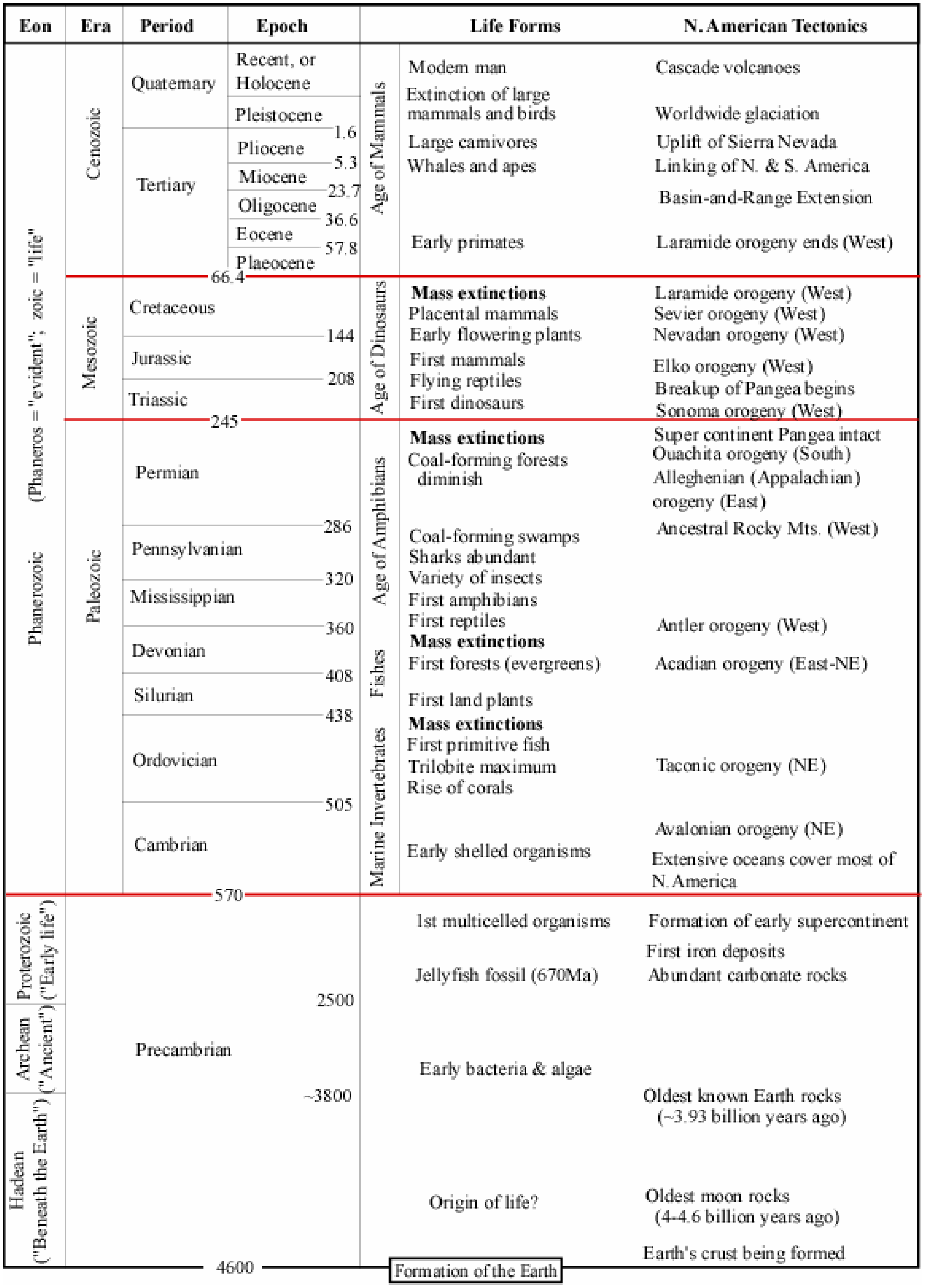


Figure 7: Geologic Time Scale. Red lines indicate major unconformities between eras. Included are major events in life history and tectonic events occurring North American continent. Absolute ages shown are in millions of years and are from the United States Geological Survey (USGS) time scale found at: http://geology.wr.usgs.gov/docs/usgsnps/gtime/timescale.html.

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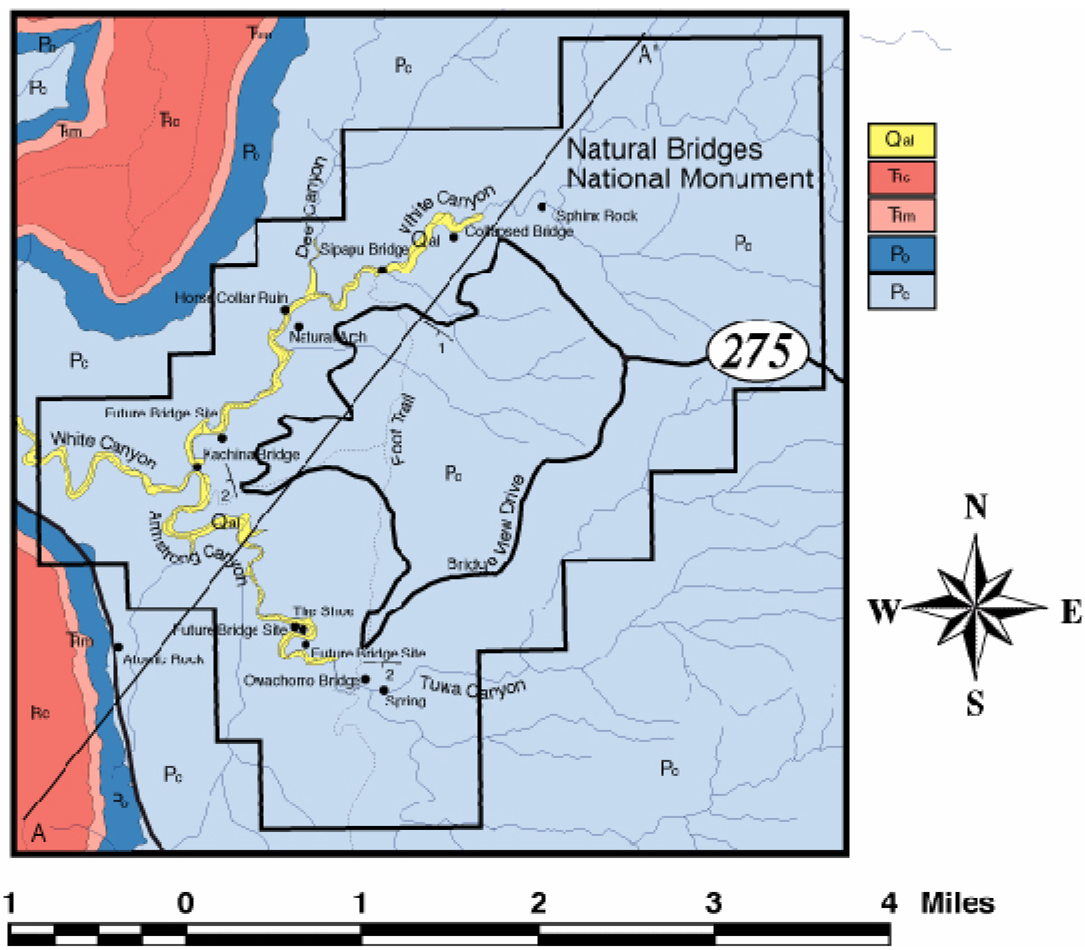
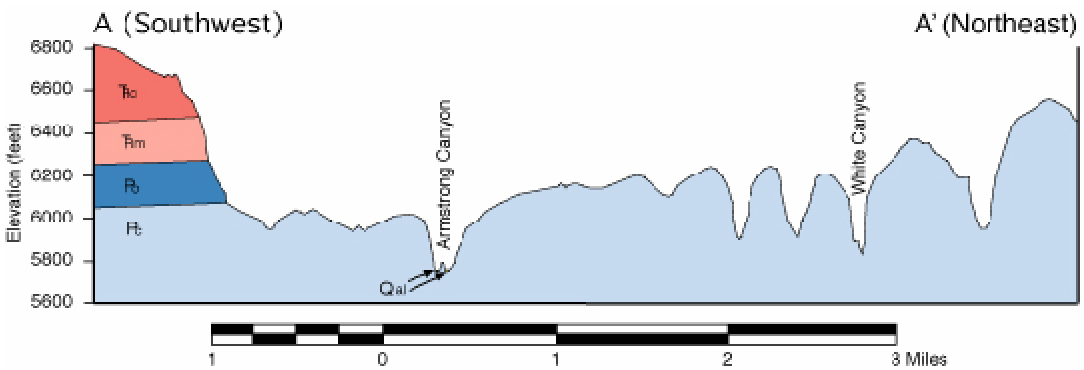
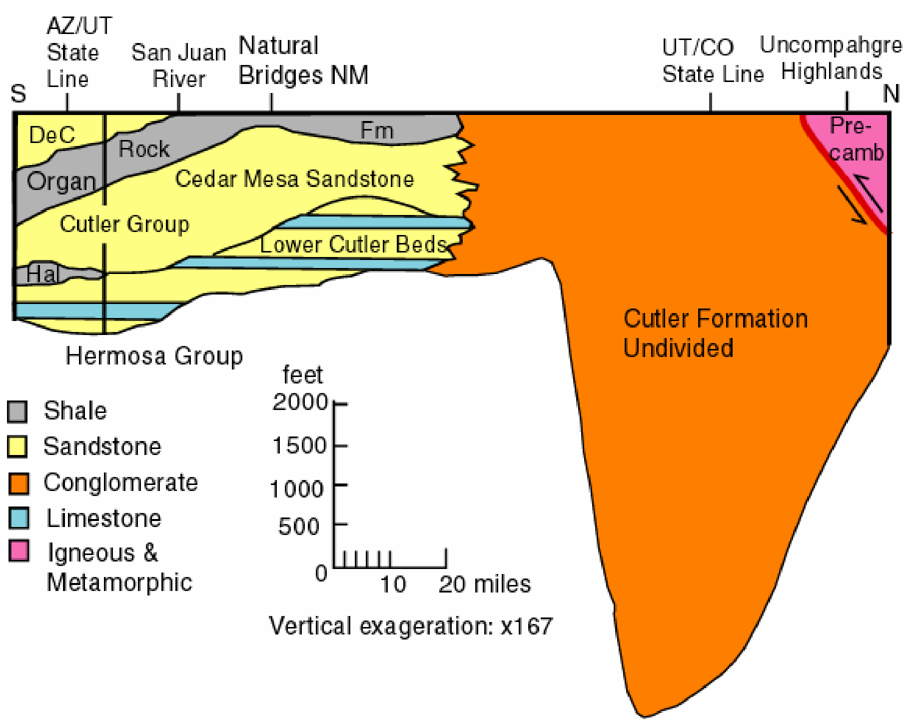
Appendix A: Geologic Map and Cross Section Graphics



The original map digitized by NPS staff to create this product was: Huntoon, Jacqueline E., 2000, Geologic map of Natural Bridges National Monument and Vicinity, Utah, NPS, unpublished, 1:24000 scale. For a detailed digital geologic map and cross sections, see included CD.



Geologic Cross Section (A). From Huntoon et al., 2000. Note flat-lying stratigraphic units.



Geologic Cross Section (B). This section shows the stratigraphic relationships of Permian strata in the Natural Bridges National Monument region. The north-south cross section line runs from the Arizona – Utah border to the Uncompahgre Highlands across the Utah – Colorado border. DeC: De Chelly Sandstone; Hal: Halgaito Formation. Modified only slightly from Stanesco *et al.*, 2000.

Appendix B: Scoping Summary

The following excerpts are from the GRE Workshop Summary for the Southeast Utah Group (SEUG) National Park, Utah, with specific attention to Natural Bridges National Monument. This summary is included as a historical document and as such contact information and web addresses referred to herein may be outdated.

Executive Summary

An inventory workshop was held for national park service units in the Southeast Utah Group (Arches NP, Canyonlands NP, Hovenweep NM, and Natural Bridges NM) from May 24- 27, 1999 to view and discuss the geologic resources, to address the status of geologic mapping by the Utah Geological Survey (UGS) for compiling both paper and digital maps, and to assess resource management issues and needs. Cooperators from the NPS Geologic Resources Division (GRD), Natural Resources Information Division (NRID), Southeast Utah Group NPS staff (interpretation, natural resources, deputy superintendents), UGS, United States Geological Survey (USGS), and Utah Geological Association (UGA) were present for the two day workshop.

Monday May 24th involved a field trip to Natural Bridges NM (NABR) led by Red Rocks College geologist Jack Stanesco with additions from Christine Turner and Pete Peterson (both of the USGS).

Tuesday May 25th involved a field trip to Canyonlands NP (CANY) led by USGS geologist George Billingsley, again with additions from Christine Turner and Pete Peterson also of the USGS.

Wednesday May 26th involved a field trip to Arches NP (ARCH) led by UGS geologist Hellmut Doelling with additions from Grant Willis (UGS) and Vince Santucci (NPS- GRD).

An on- line slide show of the highlights of these field trips can be found at http://www.nature.nps.gov/grd/geology/gri/ut/seug/field_trip_seug

Thursday May 27th involved a scoping session to present overviews of the NPS Inventory and Monitoring (I&M) program, the Geologic Resources Division, and the ongoing Geologic Resources Evaluation (GRE) for Colorado and Utah. Round table discussions involving geologic issues for the Southeast Utah Group included interpretation, the UGA Millennium 2000 guidebook featuring the geology of Utah's National and State parks, paleontological resources, the status of cooperative geologic mapping efforts, sources of available data, geologic hazards, potential future research topics, and action items generated from this meeting. Brief summaries of each follows.

Overview of Geologic Resources Evaluation

After introductions by the participants, Joe Gregson (NPS- NRID) presented an overview of the NPS I&M Program, the status of the natural resource inventories, and the geological resources inventory.

He also presented a demonstration of some of the main features of the digital geologic map for the Black Canyon of the Gunnison NM and Curecanti NRA areas in Colorado. This has become the prototype for the NPS digital geologic map model as it ideally reproduces all aspects of a paper map (i.e. it incorporates the map notes, cross sections, legend etc.) with the added benefit of being a GIS component. It is displayed in ESRI ArcView shape files and features a built- in help file system to identify the map units. It can also display scanned JPG or GIF images of the geologic cross sections supplied with the map. The cross section lines (ex. A- A') are subsequently digitized as a shape file and are hyperlinked to the scanned images.

For a recap on this process, go to: http://www.nature.nps.gov/grd/geology/gri/blca_cure/ and view the various files in the directory.

The geologists at the workshop familiar with GIS methods were quite impressed with this method of displaying geologic maps digitally; Gregson is to be commended for his accomplishments.

Bruce Heise (NPS- GRD) followed with an introduction to the NPS GRD group.

Interpretation

The GRE also aims to help promote geologic resource interpretation within the parks and GRD has staff and technology to assist in preparation of useful materials including developing site bulletins and resource management proposal (RMP) statements appropriate to promoting geology. Jim Wood (GRD) and Melanie Moreno (USGS- Menlo Park, CA) have worked with several other NPS units in developing web- based geology interpretation themes, and should be considered as a source of assistance should the park desire.

Along the lines of interpretation of geology for the SEUG, it was suggested that they consider hiring a full-time geologist to be on staff to evaluate research proposals and generally assist all interpretive areas within the SEUG to find out what issues should be addressed.

A geologist could add greatly to NABR, CANY, and ARCH because the primary theme of these parks is geologic; there would be no bridges, arches, or canyon (lands) without the underlying influence of geology and geologic processes upon this part of the world. A geologist would also certainly be active in establishing the most effective wayside exhibits aimed at informing the public about the geologic wonders of the area. A geologist can certainly assist in the presentation and interpretation of paleontologic resources and issues also.

Such a position could act as a liaison among various tour groups, researchers, field camps and professional organizations that visit the area because of the spectacular geology. Geologic hazards would also be able to be more fully understood. Obviously, effective communication skills are a highly desirable quality for any applicant.

In the absence of such a position, the GRD is most willing to assist the SEUG in any geologic matters and issues should they desire. Please contact Bruce Heise or Tim Connors to discuss further matters regarding geologic resources.

UGA Guidebook on Utah's National and State Park Areas

Doug Sprinkel of the UGA announced that a guidebook treating the geology of 27 of Utah's national and state parks and monuments will be compiled for publication in September 2000. This compilation will be a snapshot into the geology of each park and covers most facets of what the GRE is trying to develop for each park for a final report (i.e. cross sections, simplified geologic map, general discussions of rocks, structure, unique aspects of park geology, classic viewing localities). Each author will be encouraged to get with NPS staff interpreters to develop a product that aims at a wide audience (the common visitor, the technical audience and the teaching community). Authors for SEUG parks are as follows:
Arches NP: Hellmut Doelling (UGS)
Canyonlands NP: Donald Baars
Natural Bridges NM: Jackie Huntoon, Russell Dubiel, Jack Stanesco

Also, a CD- ROM will be distributed with the publication featuring road and trail logs for specific parks as well as a photo glossary and gallery. Park authors are strongly encouraged to get with NPS staff to make sure that any trail logs do follow maintained trails and do not take visitors into unauthorized areas, or places where resources are fragile and would be disturbed by increased visitation (i.e. areas with crytptogamic soils).

The photo glossary will describe certain geologic features (i.e. what is crossbedding?). These will also be available as web- downloadable Adobe Acrobat PDF files. The UGA cannot copyright this material because it is funded with state money, so it can be distributed widely and freely, which will also benefit the purposes of the GRE. Additional reprints are not a problem because of the digital nature of the publication and the UGA board is committed to additional printings as needed. UGA normally prints 1000 copies of their publications because they become dated after about five years; that will probably not be an issue for this publication. Prices for the full- color guidebook are estimated to be approximately $25/copy, and sales are expected to be high (exact estimates for Capitol Reef NM were 125 copies/year). A website for the guidebook is forthcoming in October 1999.

Field Trips will be held in September 2000. Currently, four field trips are scheduled:
Arches NP, Canyonlands NP, Dead Horse Point State Park (SP)
Antelope Island SP and Wasatch Mountain SP
Southeast Utah Group NP, Cedar Breaks NM, Snow Canyon SP and Quail Creek SP
Dinosaur NM, Flaming Gorge NRA, and Red Fleet SP

Note: Trips 1 and 2 will run concurrently and Trips 3 and 4 will also run concurrently.

Many other benefits are anticipated from this publication and are enumerated below:
This type of project could serve as a model for other states to follow to bolster tourism and book sales promoting their state and its geologic features.

Sandy Eldredge (UGS) will be targeting teaching communities for involvement in the field trips; hopefully teachers will pass on what they have learned to their young audience.

The language is intended to appeal to someone with a moderate background in geology and yet will be very informative to the educated geologist.

The publication may be able to serve as a textbook to colleges teaching Geology of National Parks (in Utah).

A welcomed by- product could be roadlogs between parks in Utah for those visiting multiple parks, perhaps with a regional synthesis summarizing how the overall picture of Utah geology has developed.

Disturbed Lands

GRD's John Burghardt has done work in Lathrop Canyon on reclaiming abandoned mineral lands (aml). His reports should be studied as a significant source of data for this area to determine if additional work needs to be performed. Dave Steensen (GRD) heads the AML program and can also be contacted.

Paleontological Resources

The field trip at Arches NP provided glimpses into the paleontological resources (dinosaur bones) near Delicate Arch. It has been suggested to keep this location low profile to minimize disturbances and potential theft or vandalism.

During the scoping session, the importance of a paleontological resource inventory for the Cedar Mountain and Morrison Formations near the Dalton Wells Quarry was discussed as being a priority. The important resources are likely to be dinosaur bones. A staff geologist or paleontologist would surely be useful for this purpose

Vince Santucci (NPS- GRD Paleontologist) will be co-authoring a "Paleontological Survey of Arches National Park" and detailing findings of resources within the park. Plants, invertebrates, and vertebrate tracksites are among the recognized paleontological resources within the Southeast Utah Group area parks.

Similar surveys have been done for Yellowstone and Death Valley NP's and have shed valuable new information on previously unrecognized resources. These surveys involve a literature review/bibliography and recognition of type specimens, species lists, and maps (which are unpublished to protect locality information), and also make park specific recommendations for protecting and preserving the resources.

The Death Valley Survey will be available soon. The Yellowstone Survey is already available on- line at:

http://www.nature.nps.gov/grd/geology/paleo/yell_survey/index.htm

and is also available as a downloadable PDF at http://www.nature.nps.gov/grd/geology/paleo/yell.pdf

Paleontological resource management plans should be produced for Southeast Utah Group involving some inventory and monitoring to identify human and natural threats to these resources. Perhaps someone on the park staff could be assigned to coordinate paleontological resource management and incorporate any findings or suggestions into the parks general management plan (GMP). It would be useful to train park staff (including interpreters and law enforcement) in resource protection, as the fossil trade "black market" has become quite lucrative for sellers and often results in illegal collecting from federal lands.

Collections taken from this area that now reside in outside repositories should be tracked down for inventory purposes. Fossils offer many interpretive themes and combine a geology/biology link and should be utilized as much as possible in interpretive programs.

Status of Geologic Mapping Efforts for the SEUG

Status of Existing Maps

It should be noted that the following paper geologic maps exist:

Arches NP ("Geologic Map of Arches National Park and vicinity, Grand County, Utah" by Hellmut H. Doelling, 1985) at 1:50,000. The area was mapped at 1:24,000 scale, but compiled at 1:50,000 scale.

Canyonlands NP ("Geologic Map of Canyonlands National Park and Vicinity, Utah" by George Billingsley, Peter Huntoon, and William J. Breed, 1982) at 1:62,500

Canyonlands NP ("Bedrock Geologic Map of Upheaval Dome, Canyonlands NP, Utah" by Gene Shoemaker, Herkenhoff and Kriens, 1997); scale unknown.

George Billingsley noted that when he worked on the Canyonlands map, he mostly compiled previous material. He thought several additions to the Quaternary deposits and the placement of joints/fractures on the maps would improve the quality of the 1982 Canyonlands map. There are also some issues regarding assignment of the Page Sandstone, and the controversy of the Dewey Bridge Member of the Entrada versus the Carmel Formation being within the map area. He thinks eventually, the entire area should be compiled at 1:24,000 to better enhance features and add to resource management.

Jackie Huntoon has told Bruce Heise that she is working on a digital coverage for Natural Bridges, but needs the hypsography (contour lines) to complete her work. Desired quadrangles that NRID has this coverage for are the following:

The Cheesebox
Woodenshoe Buttes
Kane Gulch

It is not sure if the coverage exists for the Moss Back Butte quadrangle; Joe Gregson will look into it.

Digitized Maps

The 1985 Arches map has been digitized into an ArcInfo coverage by SEUG staff. The attribute quality is unknown however, and will be researched. NPS- GRE folks will work with SEUG GIS Specialist Gery Wakefield to learn more about this coverage

The 1982 Canyonlands map is not known to have been digitized at this point and hopefully can be done by the SEUG GIS staff. George Billingsley says that the Canyonlands Natural History Association has the original line work and mylars; Diane Allen said she will contact them to see if they still have this work.

The 1997 Upheaval Dome map is digitized as an ArcInfo coverage and a copy was given to Craig Hauke (cany) from George Billingsley. It also contains cross sections and a report. A website exists for this work at: http://www.seismo.unr.edu/ftp/pub/louie/dome/98seismo/index.html.

UGS Mapping Activities in SEUG area

Currently, the UGS is mapping in Utah at three different scales:
1:24,000 for high priority areas (i.e. National and State parks)
1:100,000 for the rest of the state
1:500,000 for a compiled state geologic map

The UGS plans to complete mapping for the entire state of Utah within 10- 15 years at 1:100,000 scale. For 1:100,000 scale maps, their goal is to produce both paper and digital maps; for 1:24,000 scale maps, the only digital products will be from "special interest" areas (i.e. areas such as Southeast Utah Group and growing metropolitan St. George). Grant Willis mentioned that the UGS simply does not have enough manpower and resources to do more areas at this scale. He also reiterated that UGS mapping goals are coincident with those of the National Geologic Mapping Program.

Grant Willis talked about the status of UGS mapping activities within the Southeast Utah Group area (see Appendix C for reviewing specific index maps for each park).

30 x 60 sheets (at 1:100,000) for the area include the La Sal (greater Canyonlands area) and Moab (Arches NP) sheets, which are currently in progress (paper and digital format).

Other Sources of Natural Resources Data for the SEUG

The UGS has a significant quadrangle database that they have furnished to NRID for the entire state of Utah.

NRID has compiled a geologic bibliography for numerous parks and monuments, including all parks in the Southeast Utah Group. Visit the website at: http://165.83.36.151/biblios/geobib.nsf; user id is "geobib read", password is "anybody".

SEUG GIS specialist showed a digitized version of Hellmut Doelling's 1985 map as and ArcInfo coverage; attribution needs to be checked; other coverage's should be sought that may exist from the previous GIS specialist

GRD has several entries regarding abandoned mineral land (AML) sites in their database that should be checked for data validity and compared with park records; John Burghardt (GRD) should be contacted regarding this

The Arches NP visitor center sells a publication that has an inventory of all the arches of Arches

The UGS has compiled a CD- ROM with well locations, pipelines, etc. for the state of Utah; GRD should obtain a copy of this. Parks may also desire copies too.

Geologic Hazards

There are numerous issues related to geologic hazards in and around the Southeast Utah Group parks. Below is a brief list of some mentioned during the scoping session:

Landslide and rockfall potential along all roads that occasionally cause road closures; of special note was the problem with the main road in Arches, just above the visitor center

Landscape Arch (arch) collapsed in a few places several years ago and was recorded by a tourist

Swelling soils associated with bentonitic shale's of the Chinle, Morrison, and Mancos formations

Radon potential associated with mine closures

Earthquake potential along the Moab Fault

Potential Research Topics for Southeast Utah Group NP

A list of potential research topics includes studies of the following:

What are the connections between gypsiferous rocks and cryptobiotic soils/crusts?; why were the crust healthier on the gypsum- bearing rocks?

How long will Delicate Arch stand?

Engineering studies to determine hazards to visitors; use strain meter

Use High resolution GPS to detect moving, swelling, and collapse in areas of the parks

Rock color studies

Subsurface seismic work for voids in the Needles around synclines and salt dome structures

Locate real unconformity between Entrada Moab Tongue and abutting formations

Action Items

Many follow- up items were discussed during the course of the scoping session and are reiterated by category for quick reference.

Interpretation

More graphics and brochures emphasizing geology and targeting the average enthusiast should be developed. If Southeast Utah Group NP needs assistance with these, please consult GRD's Jim Wood (jim_f._wood@nps.gov) or Melanie Moreno at the USGS- Menlo Park, CA (mmoreno@usgs.gov).

Consider the possibility of hiring a full- time geologist to handle geologic issues for the SEUG; in the absence of this consult with GRD for assistance in geologic matters

UGA Guidebook

Attempt to plant the seeds of this concept to other states for similar publications involving local area geology. Such publications are especially useful for the GRE

Have authors prepare logs that are "sensitive" to delicate areas in the park (i.e. where less user impact is desired)

Paleontological Resources

For now, try to minimize location disclosure of vertebrate sites to minimize disturbances and the potential for theft or vandalism

Develop an in- house plan to inventory, monitor and protect significant paleontological resources from threats; assign staff to oversee especially in regard to the Dalton Wells area

Locate collections taken from the park residing in outside repositories

Geologic Mapping

Attempt to complete digital coverage for the entire SEUG area from existing maps

Locate already existing digital coverage's (like that of Doelling's 1985 Arches map)

Work closely with UGS to finish paper and digital coverage of SEUG area where maps are lacking

Work with cooperators (NABR- Jackie Huntoon) to ensure there work could be incorporated into the master plan of the GRE

Natural Resource Data Sources

Examine GRD databases for AML and disturbed lands for data validity

Attempt to locate other digital coverage's from the previous SEUG GIS specialist (Eric) for Gery Wakefield's (current SEUG GIS specialist) inventory

Miscellaneous

Review proposed research topics for future studies within Southeast Utah Group NP

Promote sensitivity to delicate resources (crusts, etc.) to researchers, and visiting park groups

List of Scoping Meeting attendees with contact information

NAME	AFFILIATION	PHONE	E-MAIL
Joe Gregson	NPS, Natural Resources Information Division	(970) 225-3559	Joe_Gregson@nps.gov
Tim Connors	NPS, Geologic Resources Division	(303) 969-2093	Tim_Connors@nps.gov
Bruce Heise	NPS, Geologic Resources Division	(303) 969-2017	Bruce_Heise@nps.gov
Christine Turner	USGS	(303) 236-1561	Cturner@usgs.gov
Fred Peterson	USGS	(303) 236-1546	Fpeterson@usgs.gov
Jack Stanesco	Red Rocks CC	(303) 914-6290	Jack.Stanesco@rrcc.cccoes.edu
Craig Hauke	NPS, CANY	(435) 259-3911 ext. 2132	Craig_hauke@nps.gov
Grant Willis	Utah Geological Survey	(801) 537-3355	Nrugs.gwillis@state.ut.us
George Billingsley	USGS-Flagstaff, AZ	(520) 556-7198	Gbillingsley@usgs.gov
Vince Santucci	NPS, Geologic Resources Division	(307) 877-4455	Vince_Santucci@nps.gov
Jim Dougan	NPS, NABR	(435) 692-1234	Jim_Dougan@nps.gov
Al Echevarria	Red Rocks CC	(303) 985-5996	Ale44@juno.com
Dave Wood	NPS, CANY	(435) 259-3911 ext. 2133	Dave_Wood@nps.gov
Traci Kolc	NPS, CANY	(435) 259-4712 ext. 18	Traci_Kolc@nps.gov
Margaret Boettcher	NPS, ARCH SCA	(435) 259-1963	Margaret_arches@hotmail.com
Clay Parcels	NPS, ARCH	(435) 259-8161 ext. 245	Clay_Parcels@nps.gov
Alicia Lafever	NPS, ARCH	(435) 259-8161 ext. 242	Alicia_Lafever@nps.gov
Adrienne Gaughan	NPS, ARCH	(435) 259-8161 ext. 286	Adrienne_Gaughan@nps.gov
Shawn Duffy	NPS, ARCH	(435) 259-7223	Shawn_Duffy@nps.gov
Murray Shoemaker	NPS, ARCH	(435) 259-8161 ext. 244	Murray_Shoemaker@nps.gov
Helmut Doelling	UGS	(435) 835-3652	None
Doug Sprinkel	UGS / UGA	(801) 782-3398	Sprinkel@vii.com
Jim Webster	NPS, ARCH	(435) 259-8161 ext. 220	Jim_Webster@nps.gov
Gery Wakefield	NPS, SEUG GIS coordinator	(435) 259-3911 ext. 2180	Gery_Wakefield@nps.gov
Phil Brueck	NPS, SEUG	(435) 259-3911 ext. 2102	Phil_Brueck@nps.gov
Bruce Rodgers	NPS, SEUG	(435) 259-3911 ext. 2130	Bruce_Rodgers@nps.gov
Diane Allen	NPS, ARCH	(435) 259-8161	Diane_Allen@nps.gov
Paul Henderson	NPS, SEUG	(435) 259-3911 ext. 2140	Paul_Henderson@nps.gov

Appendix C: Geoindicators Report

The following are excerpts (applicable to Natural Bridges National Monument) of the Geoindicators Scoping Report for Arches National Park, Canyonlands National Park, Capitol Reef National Park and Natural Bridges National Monument, compiled by Andy Pearce, 2002.

Introduction

From June 3- 5, 2002, staff of the National Park Service, Utah Geological Survey, U.S. Geological Survey, Bureau of Land Management, Northern Arizona University, and Brigham Young University participated in a geoindicators scoping meeting in Moab, Utah for four National Park Service units in southeastern Utah. The four parks were Arches National Park (ARCH), Canyonlands National Park (CANY), Capitol Reef National Park (CARE), and Natural Bridges National Monument (NABR).

Purpose of meeting

The purpose of the meeting was to bring together park staff, geoscientists, and other resource specialists to address the issue of human influences on geologic processes in the four park areas. The group used collective knowledge of the four parks' geology and natural resources to identify the geologic processes active in the parks, to identify the human activities affecting those processes, and to develop recommendations for long- term monitoring of geoindicators in conjunction with park Vital Signs monitoring.

In addition, the Northern Colorado Vital Signs Network is coming on- line in fiscal year 2002 and will be receiving its first funding for Vital Signs monitoring. The scoping meeting was timed so the Network could use the information gained during the meeting in the Vital Signs selection process.

This report summarizes the group's discussions and provides recommendations for studies to support resource management decisions, inventory and monitoring projects, and research needed to fill data gaps.

Government Performance and Results Act (GRPA) Goal Ib4

This meeting satisfies the requirements of the GPRA Goal Ib4, which is a knowledge- based goal that states, "Geological processes in 53 parks [20% of 265 parks] are inventoried and human influences that affect those processes are identified." The goal was designed to improve park managers' capabilities to make informed, science- based decisions with regards to geologic resources.

It is the intention of the goal to be the first step in a process that will eventually lead to the mitigation or elimination of human activities that severely impact geologic processes, harm geologic features, or cause critical imbalance in the ecosystem.

Because GPRA Goal Ib4 inventories only a sampling of parks, information gathered at the four parks may be used to represent other parks with similar resources or human influences on those resources, especially when findings are evaluated for Servicewide implications.

Geoindicators background information

An international Working Group of the International Union of Geological Sciences developed geoindicators as an approach for identifying rapid changes in the natural environment. The National Park Service uses geoindicators during scoping meetings as a tool to fulfill GPRA Goal Ib4. Geoindicators are measurable, quantifiable tools for assessing rapid changes in earth system processes. Geoindicators evaluate 27 earth system processes and phenomena that may undergo significant change in magnitude, frequency, trend, or rates over periods of 100 years or less and may be affected by human actions. Geoindicators guide the discussion and field observations during scoping meetings. The geoindicators scoping process for the National Park Service was developed to help determine the studies necessary to answer management questions about what is happening to the environment, why it is happening, and whether it is significant.

Aspects of ecosystem health and stability are evaluated during the geoindicators scoping process. The geologic resources of a park—soils, caves, streams, springs, beaches, volcanoes, etc.—provide the physical foundation required to sustain the biological system. Geological processes create topographic highs and lows; affect water and soil chemistries; influence soil fertility and water- holding capacities, hillside stability, and the flow regimes of surface water and groundwater. These factors, in turn, determine where and when biological processes occur, such as the timing of species reproduction, the distribution and structure of ecosystems, and the resistance and resilience of ecosystems to human impacts.

Park Selection

These parks were selected to represent the Northern Colorado Plateau Network (NPCN) of parks. The parks will be the foci of research and development for protocols associated with vital- signs monitoring at

NCPN parks and monuments. Geologic resources and processes found in these four parks are generally representative of those found throughout the rest of the NCPN, and considerable geologic research has been conducted in them previously.

Summary of Results and Recommendations

During the scoping meeting, geoindicators appropriate to Arches National Park, Canyonlands National Park, Capitol Reef National Park, and Natural Bridges National Monument were addressed. Of the 27 geoindicators, 21 were recognized as on- going processes to varying degrees in the four parks. An additional four geologic issues that are not part of the original geoindicators were also discussed (i.e., fire occurrence, atmospheric deposition, paleontological resources, and climate), as was an issue called "ecosystem response to geomorphic processes." The issues surrounding each geoindicator were identified, and participants rated the geoindicator with respect to the importance to the ecosystem, human impacts, and significance for resource managers (Geoindicators table).

During the geoindicators scoping meeting, participants identified studies to support resource management decisions, inventory and monitoring projects, and research to fill data gaps at all four parks. The recommendations that follow are not listed in any order of priority, but are intended to help guide park managers when making decisions regarding natural resource management needs. The recommendations that are listed are by no means inclusive of all possible geological research and monitoring.

Significant geoindicators

The following is a summary of the results for the 11 geoindicators that rated the highest in all three categories, as well as the recommendations for these geoindicators that were proposed during the meeting.

Desert surface crusts (biological and physiochemical) and pavements

Biological soil crusts composed of varying proportions of cyanobacteria, lichens, and mosses are important and widespread components of terrestrial ecosystems in all four parks, and greatly benefit soil quality and ecosystem function. They increase water infiltration in some soil types, stabilize soils, fix atmospheric nitrogen for vascular plants, provide carbon to the interspaces between vegetation, secrete metals that stimulate plant growth, capture nutrient- carrying dust, and increase soil temperatures by decreasing surface albedo.

They affect vegetation structure directly due to effects on soil stability, seedbed characteristics, and safe- site availability, and indirectly through effects on soil temperature and on water and nutrient availability. Decreases in the abundance of biological soil crusts relative to physicochemical crusts (which can protect soils from wind erosion but not water erosion, and do not perform other ecological functions of biological crusts) can indicate increased susceptibility of soils to erosion and decreased functioning of other ecosystem processes associated with biological crusts.

Human impacts

Off- trail use by visitors, past trampling by cattle in Arches and Canyonlands national parks, and present trampling by cattle in Capitol Reef National Park have damaged soil crusts significantly in some areas. Soil nutrient cycles, as well as most other benefits of biological soil crusts, have been compromised in these areas.

Recommendations

1. Inventory condition and distribution of biological soil crusts.
2. Investigate connection between ecosystem function and biological crusts.
3. Map crust communities in relation to environmental factors.
4. Study crust recovery rates and susceptibility to change.
5. Study crust population dynamics and conditions.

Wind erosion and deposition

In addition to water, wind is a major force that can redistribute soil and soil resources (e.g., litter, organic matter, and nutrients) within and among ecosystems. Erosion and deposition by wind is important in all four parks and can be accelerated by human activities. Accelerated losses of soil and soil resources by erosion can indicate degradation of arid- land ecosystems because ecosystem health is dependent on the retention of these resources.

Human impacts

Trampling and vegetation alteration by livestock as well as human recreational activities such as hiking, biking, and driving off of established trails and roads can destabilize soils and increase soil susceptibility to wind erosion. Some localized heavy visitation areas within parks have seen crust death by burial from windblown sands when nearby crusts have been trampled, such as in the Windows area of Arches National Park

In addition, wind erosion and sediment transport may be strongly impacted by land- use practices outside the parks. Eolian sand from disturbed surfaces may saltate onto undisturbed ground, burying and killing vegetation and/or biological soil crusts, or breaking biological soil crusts to expose more soil to erosion.

Because park management practices limit or prohibit off- road travel, human impacts within the parks primarily are associated with off- trail hiking in high- use areas. Where livestock grazing or trailing is still permitted (e.g., CARE), accelerated soil erosion can be more extensive.

Recommendations
1. Monitor movement of soil materials (see Recommendations table).
2. Investigate ecosystem consequences of movement (**Contact:** Jason Neff, 303- 236- 1306, jneff@usgs.gov)
3. Investigate natural range of variability of soil movement in relation to landscape configuration and characteristics. (**Contact:** Jason Neff, 303- 236- 1306, jneff@usgs.gov)

Stream channel morphology

The morphology of stream channels impacts the vegetative structure of the riparian corridor, affects the height of the water table, and affects the energy of water flow downstream (which affects erosion rate and water quality). Stream channels are vital components of aquatic and riparian ecosystems in these arid- land parks.

Human Impacts
Potential for human impact on stream channel morphology is great. These impacts include building parking lots and structures in or near channels, building structures in floodplains (e.g., culverts and bridges), livestock grazing in uplands and stream channels, roads and trails up streambeds, introduction of exotic species, and impacts from flow regulation and diversion.

Recommendations
1. Conduct hydrologic condition assessment to identify actual and potential "problem reaches" for prioritized monitoring.
2. Once "problem reaches" are identified, monitor with repeat aerial photographs.
3. Once "problem reaches" are identified, monitor with repeated cross- sections. Some data are available for Capitol Reef, Canyonlands, and Arches national parks. (See Recommendations table).

Stream sediment erosion, storage and load

Participants added "erosion" in order to clarify and encompass the total geomorphic picture regarding stream function. The original title is "stream sediment storage and load." This geoindicator is important to the ecosystem because sediment loads and distribution affect aquatic and riparian ecosystems, and because sediment loading can result in changes to channel morphology and overbank flooding frequency.

Human impacts
The potential for human impact to stream sediment erosion, storage, and load is great. These impacts include building parking lots and structures in or near channels, building structures (e.g., culverts and bridges) in floodplains, grazing in uplands and stream channels, roads and trails up streambeds, introduction of exotic species, and impacts from flow regulation and diversion.

Recommendations
1. Conduct research concerning ungaged stream sediment storage and load. There are no data available except on the main stem of the Colorado River at Cisco, Utah, and the Green River at Green River, Utah.
2. Measure sediment load on streams of high interest for comparative assessment. Data will provide information for making management decision.

Streamflow

Streamflow is critical to the maintenance of aquatic and riparian ecosystems. Streamflow impacts the structure of the riparian corridor, affects the height of the water table, and affects water quality and erosion rates.

Human impacts
The potential for human impact on streamflow is great. These impacts include building parking lots and structures in or near channels, building structures (e.g., culverts and bridges) in floodplains, grazing in uplands and stream channels, roads and trails up streambeds, introduction of exotic species, and impacts from flow regulation and diversion.

Recommendations
1. Identify important hydrologic systems that would benefit from knowledge of streamflow. Existing gauging stations are located on the Green River (Green River, Utah), San Rafael River (near Green River, Utah.), Fremont River (at Cainville, Utah, and above Park at Pine Creek.), and on the Muddy River. Many other gauging stations exist (see USGS Web site). Additional data exists for streams in Capitol Reef National Park and for Courthouse Wash in Arches National Park. Other relevant data exists with the local U.S. Geological Survey, Water Resources Division.
2. Research effects of land use and climatic variation on streamflow.
3. Investigate paleoflood hydrology.

Surface water quality

For detailed understanding of the issues and what has been done with regards to water quality data for the four NPS units, see the June, 2002, trip report prepared by Don Weeks in Appendix J. There are a number of park-specific water resource reports cited in the report that are particularly pertinent.

Human impacts
The potential for negative affects on groundwater quality by human activity is significant. The following are specific issues that could impact groundwater quality:
- Herbicide use to decrease tamarisk populations.
- Trespass cattle at springs.
- Abandoned oil and gas wells within and close to NPS boundaries may result in saline waters infiltrating into groundwater supplies.
- Abandoned uranium mines and mills.

- Impacts from recreational uses (these have not been quantified).

Human impacts in Natural Bridges National Park
- Abandoned copper and uranium mines.

Recommendation
1. Obtain information about existing baseline water quality data for all four parks (**Contact**: Don Weeks, 303- 987- 6640, don_weeks@nps.gov). Also see Don Weeks June, 2002, trip report in Appendix J.

Wetlands extent, structure, and hydrology

Wetlands are important ecosystems because they stabilize streambanks, act as filters to improve water quality, attenuate floodwaters, enhance biodiversity (important habitat for amphibians, reptiles, birds, and Threatened and Endangered Species), are highly productive in terms of biomass and nutrient productivity, and are valuable water sources for wildlife and recreationists.

Human impacts
The potential for human impacts on wetlands is great. These impacts include building parking lots and structures in or near channels, building structures (e.g., culverts and bridges) in floodplains, grazing in uplands and stream channels, roads and trails up streambeds, introduction of exotic species, and impacts from flow regulation and diversion. In addition, agricultural activities and past extirpation of beaver have affected wetlands.

Recommendations
1. Inventory location, character, and conditions of wetlands in all four parks.
2. Inventory distribution of exotic species in wetlands.
3. Monitor groundwater levels and surface elevations.
4. Investigate age- structure and populations of woody riparian plants in relation to land use history.
5. Investigate links between amphibian health attributes and wetland health.

Groundwater quality

The quality of groundwater in the parks has a high impact on hanging gardens, which are located in all four parks. Hanging gardens are unique features that contain rare plant species, and provide important wildlife habitat. Groundwater quality is also an issue for safety and health regarding water quality for human use. To further understand what the issues are and what has been done with regards to water quality data for the four NPS units, see Appendix J.

Human impacts
The potential for negative affects on groundwater by human activity is significant. All four parks identified specific issues that could impact groundwater quality.

Human impacts in Natural Bridges National Monument
- The impacts of copper and uranium mining and oil and gas drilling are unknown.

Recommendations
1. Locate and inventory all seeps, springs, and hanging gardens.
2. Prioritize seeps, springs, and hanging gardens for assessment of water quality.
3. Acquire plugging records of oil and gas wells potentially connected to park groundwater systems **(Contact:** Bob Higgins, 303- 969- 2018, bob_higgins@nps.gov).
4. Use geochemical indicators to investigate groundwater flow areas, flow directions and recharge area, and groundwater age.
5. Identify and study potential sources for groundwater quality impacts at all four parks, including those listed above (**Contact**: Don Weeks, 303- 987- 6640, don_weeks@nps.gov). (See Appendix J.)

Groundwater level and discharge

Outside the river corridors in Canyonlands and Capitol Reef national parks, groundwater supplies much of the water available for wildlife, and supplies 100% of the park's water supply for human use.

Human impacts
Groundwater is a limited resource, and the potential for human impact is great. Current human impacts are poorly understood.

Recommendations
1. Inventory and research are needed concerning groundwater quality, level, and discharge.
2. Install transducers and dataloggers in wells.
3. Develop methods for measuring water discharge from seeps and hanging gardens **(Contact:** Bob Webb, 520- 670- 6671, rhwebb@usgs.gov).
4. Investigate additional methods to characterize groundwater recharge areas and flow directions **(Contacts:** Charlie Schelz, 435- 719- 2135, charlie_schelz@nps.gov and Rod Parnell, 928- 523- 3329, roderic.parnell@nau.edu).

Soil quality

Soil quality affects moisture retention, nutrient cycling, soil- food webs, and aggregate structure. Soil also provides biogeochemical and hydrologic support for terrestrial productivity, especially vegetation growth. Soil quality degradation results in loss of certain ecosystem functions, such as nutrient cycling.

Human impacts
Due to past and present grazing in the parks, nutrient cycles have not recovered.

Recommendations
1. Assess existing soil- crust conditions in relation to potential (as an indicator of soil quality) and in relation to soil maps.

2. Repeatedly measure soil quality in disturbed sites to gain understanding of recovery rates in relation to environmental factors, such as soil texture, topographic position, and climate.
3. Quantify natural range of variability in quality in relation to environmental factors.
4. Develop predictive model for potential biological soil crust distribution/structure/function in relation to environmental factors, such as soil texture, soil chemistry, topographic position, and climate.
5. Investigate susceptibility to change (e.g., climate and UV).
6. Study resistance and resilience of soil to human disturbances.

Soil and sediment erosion and deposition by water

During the discussion of this geoindicator, participants chose to focus on water transport and deposition, therefore the words, "and deposition by water" were added to this geoindicator. Transport and/or loss of soil may result in degradation of soil quality (see Soil quality geoindicator).

Human impacts
In general, past grazing practices has caused soil erosion in all four parks. There is still occasional trespass of cattle in Arches and Canyonlands national parks and Natural Brides National Monument.

Recommendations
1. Investigate/develop methods for monitoring erosion and deposition quantitatively and affordably, and determine the best locations to monitor **(Contact:** Bob Webb, 520- 670- 6671, rhwebb@usgs.gov).
2. Assess conditions of soil erosion (e.g., qualitative hydrologic function).

Ecosystem response to geomorphic processes

Because many types of ecosystems are highly dependent on the geomorphic process and substrate, ecosystem response to geomorphic processes is highly important to park ecosystems.

Disturbance to ecosystems is inevitable, whether the disturbance is human or natural caused. Management actions that attempt to mitigate disturbances, and particularly restoration of disturbed areas, may be influenced by the types of geomorphic processes involved and/or the nature of geomorphic substrates.

Knowledge of predicted ecosystem responses to disturbances may affect the decision of whether to actively rehabilitate a disturbed site or whether to allow it to recover naturally. If active rehabilitation or restoration is chosen, this knowledge should determine what types of species are suitable for the underlying geomorphic conditions. Land- use practices, as well as climatic fluctuations may have an impact on ecosystem response. The perceived significance by managers depends upon need in the wake of an important disturbance that may instigate a management response.
(**Contacts**: Bob Webb, 520- 670- 6671, rhwebb@usgs.gov; and Rod Parnell, 928- 523- 3329, roderic.parnell@nau.edu)

Recommendations
1. Acquire high quality surficial geology, soil, and vegetation maps for all four parks. Current availability of soil and geologic mapping varies among the parks.
2. Determine what to monitor, where, and with what attributes/indicators.
3. Research spatial and temporal relations among ecosystem structure and function, geologic substrates, and geomorphic processes.
4. Assess change- detection methods

List of Participants

National Park Service

Tom Clark, Capitol Reef National Park, Torrey, Utah
Craig Hauke, Southeast Utah Group, Moab Utah
Bob Higgins, Geologic Resources Division, Lakewood, Colorado
Alison Koch, Fossil Butte National Monument, Kemmerer, Wyoming
Greg McDonald, Geologic Resources Division, Lakewood, Colorado
Mark Miller, Northern Colorado Plateau Network, Moab, Utah
Mary Moran, Southeast Utah Group, Moab, Utah
Andy Pearce, Aztec Ruins National Monument, Aztec, New Mexico
Bruce Rodgers, Southeast Utah Group, Moab, Utah
Vince Santucci, Fossil Butte National Monument, Kemmerer, Wyoming
Charlie Schelz, Southeast Utah Group, Moab, Utah
Dave Sharrow, Zion National Park, Kanab, Utah
Gery Wakefield, Southeast Utah Group, Moab Utah
Don Weeks, Water Resources Division, Lakewood, Colorado

U.S. Geological Survey

Jayne Belnap, Moab, Utah
Jason Neff, Denver, Colorado
Marith Reheis, Denver, Colorado
Rich Reynolds, Denver, Colorado
Bob Webb, Tucson, Arizona

Other

Charles Bishop, Utah Geological Survey, Salt Lake City, Utah
Larry Coats, Northern Arizona University, Flagstaff, Arizona
Hugh Hurlow, Utah Geological Survey, Salt Lake City, Utah
Lynn Jackson, Bureau of Land Management, Moab, Utah
Katie KellerLynn, NPS Contractor, Estes Park, Colorado
Dan Martin, Brigham Young University, Provo, Utah
Tom Morris, Brigham Young University, Provo, Utah
Rod Parnell, Northern Arizona University, Flagstaff, Arizona
Doug Powell, Bureau of Land Management, Kanab, Utah
Mike Young, Westfield State College, Westfield, Massachusetts

Geoindicator table for Natural Bridges National Monument.

Geoindicators	Importance to park ecosystem	Human Impacts	Significance to natural resource managers
ARID AND SEMIARID			
Soil crusts and pavements	5	5	5
Dune formation and reactivation	1	1	1
Dust storm magnitude, duration and frequency	1	5 1	3
Wind erosion (and deposition)	5	5 1	
SURFACE WATER			
Stream channel morphology	5	5	5
Stream sediment storage and load	5	5	5
Streamflow	5	5	5
Surface water quality	5	5	5
Wetlands extent, structure, hydrology	5	5	5
GROUNDWATER			
Groundwater quality	5	U	4
Groundwater level (and discharge)	5	5	5
SOILS			
Soil quality	5	1 5	5
Soil and sediment erosion (and deposition by water)	4	1 5	4
Sediment sequence and composition	1	4	3
HAZARDS			
Landslides, rockfalls, debris flows	2	1	1
Seismicity	1	0	1
Surface displacement (salt dissolution)	1	0	1
Fire occurrence	1	5	1
OTHER			
Atmospheric deposition (N, SO_4)	1	3	1
Paleontological resources	1	3	3
Climate	5	1	5
Ecosystem structure and function characteristics as integrated indicators of geophysical (i) environments, (ii) processes, and (iii) changes/disturbances.	5	5#	5

0 - Not Applicable (N/A)
1 - LOW or no substantial influence on, or utility for
3 - MODERATELY influenced by, or has some utility for
5 - HIGHLY influenced by, or with important utility for
U - Unknown; may require study to determine applicability

Natural Bridges National Monument

Geologic Resource Evaluation Report
NPS D47, September 2004

National Park Service

Director • Fran P. Mainella

Natural Resource Stewardship and Science

Associate Director • Michael A. Soukup
Deputy Associate Director • Abigail B. Miller

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The Natural Resource Program Center consists of six divisions: Air Resources, Biological Resource Management, Environmental Quality, Geologic Resources, Natural Resource Information, and Water Resources Divisions.

Geologic Resources Division

The Geologic Resources Division, in partnership with parks and others, works to protect, preserve, and understand the geologic resources of the National Park System and to protect park resources from the adverse affects of mineral development in and adjacent to parks. One of the functions of the Division, carried out in the Planning Evaluation and Permits Branch is the Geologic Resource Evaluation Program. This program develops digitized geologic maps, reports, and bibliographies for parks.

Chief • David B. Shaver
Planning Evaluation and Permits Branch Chief • Carol McCoy

Credits

Author • Trista Thornberrry-Ehrlich
Editing • Lisa Norby and Sid Covington
Layout • Melanie Ransmeier

Map Digitizing • Stephanie O'Meara

The *Geologic Resource Evaluation Report for Glacier National Park* is published electronically on the World Wide Web, please see www2.nature.nps.gov/geology/inventory/reports. For a printed copy write to:

National Park Service
Geologic Resources Division
Natural Resource Program Center
P.O. Box 25287
Denver, CO 80225-0287

National Park Service
Technical Information Center
Denver Service Center
P.O. Box 25287
Denver, CO 80225-0287

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National Park Service
U.S. Department of the Interior

Natural Resource Program Center

Geologic Resources Division
National Park Service
P.O. Box 25287
Denver, CO 80225